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PETROLOGY FOR STUDENTS:

AN INTRODUCTION TO THE STUDY OF ROCKS UNDER THE MICROSCOPE.

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PREFACE TO THIRD EDITION.

THE following work, now offered in a further revised edition, has been written to serve as a guide to the study of rocks in thin slices, and is of course assumed to be supplemented throughout by demonstrations on actual specimens. Since it is designed primarily for the use of English-speaking students, examples are chosen, so far as is possible, from British and North American rocks; and a like remark applies to the numerous references to original authorities which are inserted in foot-notes.

No systematic account is given of the crystallographic and optical properties of minerals. This is rendered unnecessary by such books as Iddings' translation of Rosenbusch's well-known work and Hatch's translation of the same author's tables. In particular, I have made no explicit reference to the use of convergent light.

In view of the difficulty of representing rock-sections adequately by means of process-blocks, I have often cited

the coloured plates in some standard works of reference, to which most students will have access. The figures given on the following pages are selected chiefly to illustrate simple structural characters, and some of them are necessarily rather diagrammatic. A number of new figures have been added for the present edition, and a few of the old ones have been withdrawn.

A. H.

St John's College, Cambridge.
    October, 1902.

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ABBREVIATIONS.

G.M. = Geological Magazine.

M.M. = Mineralogical Magazine.

Q.J.G.S. = Quarterly Journal of Geological Society.

A.J.S. = American Journal of Science.

CHAPTER I.

INTRODUCTION.

In this chapter will be included some notes on the optical properties of minerals, which may be of use to a novice; but there will be no attempt to supersede the use of books dealing systematically with the subject.

Microscope. We shall assume the use of a microscope specially adapted for petrological work, and therefore fitted with polarizing and analysing prisms, rotating stage with graduated circle and index, and 'cross-wires' of spider's web properly adjusted in the focus of the eye-piece. The sub-stage mirrors attached to such instruments usually have a flat and a concave face. With day-light the flat face should be used; with artificial light things should be so arranged that the mirror, used with the concave face, gives as nearly parallel rays as possible.

A double nose-piece, to carry two objectives, is very useful, although it usually gives very imperfect centring for high powers. The most useful objectives are a 1 inch or $1\frac{1}{2}$ inch and a $\frac{1}{4}$ inch, but for many purposes a $\frac{1}{8}$ inch is also very desirable. For minute objects, such as the 'crystallites' in glassy rocks and the fluid-pores in crystals, a high power is indispensable, and for very fine-textured sedimentary rocks an immersion-lens offers great advantages.

A selenite-plate, a quartz-wedge, and other special pieces of apparatus will be of use for various purposes. The methods

involving their use may be found in the mineralogical text-books ; where too the student will find guidance as to the examination of crystal-slices by convergent light.

Form of section of a crystal and cleavage-traces.
A well-formed crystal gives in a thin slice a *polygonal section*, the nature of which depends not only upon the forms present on the crystal, but also on the direction of the section and on its position in the crystal, as, *e.g.* whether it cuts through the centre or only truncates an edge or corner. Again, the same shape of section may be obtained from very different crystals. Nevertheless, if several crystals of one mineral are present in a rock-slice, we can by comparison of the several polygonal sections obtain a good idea of the kind of crystal which they represent. Further, if by optical or other means we can determine approximately the crystallographic direction in which a particular crystal is cut, we can usually ascertain what faces are represented by the several sides of the polygon.

For this purpose we may require to measure the angle at which two sides meet, and this is easily done with a microscope provided with a rotating stage and graduated circle. Bring the angle to the intersection of the cross-wires, adjust one of the two sides to coincide with one of the cross-wires, and read the figure at the index of the circle. Then rotate until the other side is brought to coincide with the same cross-wire, and read the new figure. The angle turned through is the angle between the two sides of the section.

This angle is the same as that between the corresponding faces of the crystal only provided the plane of section cuts these two faces perpendicularly. For a section nearly perpendicular to the two faces, however, the error will not be great.

In consequence of the mechanical forces which affect rock-masses, and also as a result of the process of grinding rock-slices, the minerals often become more or less fractured or even shattered. In a strictly homogeneous substance the resulting cracks are irregular, but if there be directions of minimum cohesion in crystals (cleavage), the cracks will tend to follow such directions, and will appear in a thin slice as fine parallel lines representing the *traces of the cleavage-planes*

on the plane of section. The regularity and continuity of the cracks give an indication of the degree of perfection of the cleavage-structure, but it must also be borne in mind that a cleavage making only a small angle with the plane of section will, as a rule, not be shewn in a slice.

In the case of a mineral like augite or hornblende, with two directions of perfect cleavage, the angle which the two sets of planes make with one another is, of course, a specific character of the mineral, or at least characteristic of a group of minerals, such as the pyroxenes or the amphiboles. In a slice perpendicular to both the cleavages the traces will shew the true angle ; for any other direction of section the angle between the cleavage-traces will be different, but it will not vary greatly for slices nearly perpendicular to both the cleavages, and will often suffice for discrimination, as for instance between the $87°$ of the pyroxenes and the $55\frac{1}{2}°$ of the amphiboles. In a slice parallel to the intersection of the two cleavages the two sets of cleavage-traces reduce to one, and a slice of a mineral such as augite or hornblende which exhibits but one set of cleavage-traces may be assumed to be nearly parallel to the intersection of the cleavages.

A mineral not possessing any good cleavage often shews irregular cracks in rock-slices (*e.g.* quartz and usually olivine). This is especially the case in brittle minerals.

Transparency, colours, and refractive indices of minerals. Only a few rock-forming minerals remain opaque even in the thinnest slices : such are graphite, magnetite, pyrites, and pyrrhotite ; usually hæmatite, ilmenite, limonite, and kaolin ; sometimes chromite or picotite. These should always be examined in reflected light ; the lustre and colour, combined with the forms of the sections and sometimes the evidence of cleavage, will usually suffice to identify any of these minerals. The great majority of rock-forming minerals become transparent in thin slices. Those which seen in hand-specimens of rocks appear opaque, are often strongly coloured in slices, while those which in hand-specimens shew colours are frequently colourless in thin slices. In the case of many minerals these 'absorption-tints' are thoroughly characteristic,

but still more so are the differences of colour (pleochroism) in one and the same crystal according to the direction of the slice and the direction of vibration of a polarized beam traversing it, as noticed below.

The colours ascribed to minerals in the following pages and the epithet 'colourless' apply to thin slices of the minerals.

Apart from colour, the aspect of a mineral as seen in thin slices by natural light varies greatly according to its *refractive index*[1], and it is of great importance for the student to learn to appreciate at a glance the effects due to a high or a low refractive index.

If a thin slice of a single crystal be mounted by itself in some medium of the same colour and refractive index as the crystal, its boundaries and surface-characters will be invisible, while its internal structure may be studied to the best advantage. Quartz mounted in Canada balsam (both colourless and of very nearly the same refractive index) is almost invisible. If olivine, a colourless mineral of much higher refractive index, be mounted in balsam, its boundaries and the slight roughness of its polished surface will be very apparent[2]. In ordinary rock-slices, mounted in balsam, a roughened or 'shagreened' appearance may be taken as the mark of a mineral having a refractive index considerably higher than that of the medium used.

Again, a highly refringent mineral surrounded in the slice by others less highly refringent is seen to be more strongly illuminated than these, and this brightness is made more conspicuous by a dark boundary which is deeper in proportion to the difference in refractive index between the mineral in question and its surroundings. For these reasons a highly refringent crystal seems to stand out in relief against the rest of the slice (fig. 1, *k*).

[1] By this must be understood its *mean* refractive index. A crystal of any system other than the regular has in any section two refractive indices, the magnitudes of which depend further upon the direction of the section; but these differences in any one mineral are usually small as compared with the differences between the mean indices in different minerals.

[2] Cohen (3), pl. xlviii, compare figs. 1 and 2.

Such considerations must be borne in mind in examining the minute inclusions in which many crystals abound. These inclusions may be of gas, of liquid (usually with a gaseous bubble), of glass, or a crystal of some other mineral; and these may be distinguished by observing that the depth of the dark border depends upon the difference in refractive index between
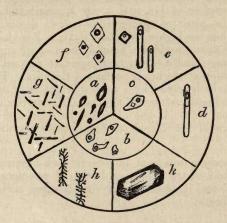

FIG. 1. VARIOUS MICROSCOPIC INCLUSIONS, HIGHLY MAGNIFIED.

a. Gas-pores; in obsidian. *b*. Fluid-pores with bubbles; in quartz. *c*. Fluid-pore with bubble and cube of salt; in quartz. *d*. Fluid-cavity in form of 'negative crystal,' containing two fluids and bubble; in quartz. *e*. Fluid-cavities in form of 'negative crystals,' with bubbles; in quartz. *f*. Glass-inclusions in form of 'negative crystals,' with bubbles; in quartz. *g*. Schiller-inclusions consisting of three sets of flat 'negative crystals' filled with opaque iron-oxide; in felspar. *h*. Schiller-inclusions consisting of 'negative crystals' partly occupied by a dendritic growth of iron-oxide; in olivine. *k*. Zircon-crystal enclosed in quartz and itself enclosing an apatite-needle.

the enclosing and the enclosed substance[1] (fig. 1). The most strongly marked border is seen when a gaseous is enclosed by a solid substance (*a*). A liquid-inclusion in a crystal has a

[1] For figures of various inclusions in crystals see Cohen (3), pl. VIII—XIII; Rosenbusch-Iddings, pl. VI, VII; Sorby, *Q. J. G. S.* (1858) xiv, pl. XVI—XIX; Ward, *ibid.* (1875) xxxi, pl. xxx.

less marked boundary, but a bubble of vapour in the liquid is strongly accentuated (*b—e*). A glass-inclusion is still less strongly marked off from its enclosing crystal, while a gas-bubble contained in it shews a very deep black border (*f*).

When two minerals (or a mineral and Canada balsam) are in contact with one another in a thin slice in such a position that their surface of junction is cut approximately at right angles by the plane of section, it is easy to determine which of the two has the higher refractive index. For this purpose the illumination should be limited by a diaphragm placed below the stage, and a high-power objective focused upon the line of junction at the upper surface of the slice. This line is then seen to be bordered by a narrow bright band on the side of the more highly refringent mineral and a narrow dark band on the other side. If the objective be depressed until the lower surface of the slice is in focus, these appearances are reversed.

The refractive indices of the several rock-forming minerals may be found in the tables or books of reference, but the student will find it useful to carry in his mind such a list as that given below.

Refractive indices of the common rock-forming minerals.

Very low (1·43—1·51) : tridymite, sodalite, analcime and most other zeolites, (volcanic glasses), leucite.

Low (1·52—1·63) : felspars, nepheline, quartz, (Canada balsam), micas, calcite, dolomite, wollastonite, actinolite, melilite.

Moderate (1·63—1·645) : apatite, tourmaline, andalusite, horn-blende.

High (1·68—1·8) : olivine, sillimanite, pyroxenes, zoisite, idocrase, epidote, garnets.

Very high (1·9—1·95) : sphene, zircon.

Extremely high (2·0—2·7) : chromite, rutile.

Extinction between crossed nicols. When the polarizing and analysing Nicol's prisms are used together, with their planes of vibration at right angles to one another

('crossed nicols')[1], if no object be interposed, there is total darkness ('extinction'), and the same is the case when a slice of any vitreous substance, such as obsidian, is placed on the stage. If, however, a slice of a crystal of any system other than the regular is interposed, there is in general more or less illumination transmitted, and often bright colours. On rotating the stage[2] carrying the object, it is found that extinction takes place for four positions during a complete rotation, these being at intervals of a right angle. In other words, there are two *axes of extinction* at right angles to one another and the slice remains dark only while these axes are parallel to the planes of vibration of the nicols, which are indicated by the cross-wires in the eye-piece. If we rotate the slice into a position of extinction and then remove the nicols, the cross-wires will mark the axes of extinction in the crystal-slice.

Without attempting to deal fully with this branch of physical optics[3], we may remark that all the optical properties of a crystal are related to three straight lines conceived as drawn within the crystal at right angles to one another (the *axes of optic elasticity*) and to a certain ellipsoid having these three straight lines for axes (the *ellipsoid of optic elasticity*). The positions of the three axes may vary in different minerals, but they must always conform to the symmetry proper to the system, and the same is true of the relative lengths of the axes of the ellipsoid. The plane of section of any slice cuts the ellipsoid in an ellipse, the form and position of which depend upon the direction of the section (*ellipse of optic elasticity*), and the axes of extinction are the axes of this ellipse.

In certain cases the ellipse of optic elasticity may be a

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[1] In using the two Nicol's prisms, it should always be ascertained that they are crossed. For this purpose the rotating prisms are usually provided with catches in the proper positions, but the true test is total darkness when no object is interposed.

[2] In some microscopes, such as that devised by Mr A. Dick, the stage is fixed, and the two nicols rotate, retaining their relative position, an arrangement with several advantages. We shall assume for distinctness that the stage is made to rotate, as in the most usual models.

[3] The student is referred for this to such a book as Rosenbusch (transl. Iddings), *Microscopical Physiography of the Rock-making Minerals* (1888), London.

circle. For this any diameter is an axis, and accordingly we find that such a slice gives extinction throughout the complete rotation. In crystals of the triclinic, monoclinic, and rhombic systems there are two directions of section which give this result. They are perpendicular respectively to two straight lines in the crystal (the *optic axes*), which lie in the plane of two of the axes of optic elasticity, and are symmetrically disposed towards them. In crystals of the tetragonal and rhombohedral systems the two optic axes coincide with one another and with the unique crystallographic axis, and only slices perpendicular to this give total darkness. In the regular system, the ellipsoid being a sphere, the ellipse is always a circle, and all slices give total darkness between crossed nicols.

Crystals of the regular system are spoken of as singly refracting or optically isotropic, and their optical properties[1] are similar to those of a glassy or colloid substance. Crystals of the other systems are doubly refracting or birefringent, and they are divided into uniaxial or biaxial according as they have one or two optic axes.

It is evident that the chance of a slice cut at random from a birefringent crystal being perpendicular to an optic axis is very small. If more than one crystal of a given mineral be present in a rock-slice, and all remain perfectly dark between crossed nicols throughout a rotation, it is a safe conclusion that the mineral is a singly refracting one.

Straight and oblique extinction. By bearing in mind that the ellipsoid of optic elasticity, and consequently all the optical properties of a crystal, must conform to the laws of symmetry proper to the crystal-system of the mineral, we can foresee all the important points as regards the position of the axes of extinction in crystals of the different systems cut in various directions. For instance, a longitudinal section of a prism of apatite (a hexagonal mineral) will extinguish when its length is parallel to either of the cross-wires : this is *straight extinction*. A longitudinal section of a prism of

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[1] That is, such of them as we are here concerned with.

albite (a triclinic mineral) will, on the other hand, have axes of extinction inclined at some angle to its length : this is *oblique extinction*. It is to be noticed that these terms have no meaning unless it is stated or clearly understood from what direction in the crystal the obliquity is reckoned. In these examples we reckoned with reference to one of the crystallographic axes defined by the traces of known crystal-faces. Another character often utilised is the cleavage. Thus in a monoclinic mineral with prismatic cleavages, such as hornblende, we select a crystal so cut that the two cleavages give only one set of parallel traces. These traces are then parallel to one of the crystallographic axes (the vertical axis), and we examine the position of extinction with reference to this. First we bring the cleavage-traces parallel to one of the cross-wires, removing if necessary for this purpose one or both of the nicols, and note the figure indicated on the graduated circle. Then, with crossed nicols, we rotate until the crystal becomes dark, and again note the figure. The angle through which we have turned is the *extinction-angle*. Observe that if a rotation through, say, 15° in one direction gives extinction, a rotation through 75° in the opposite direction would have given the same. For most purposes we do not need to distinguish between the two directions of rotation, but take merely the smaller of the two angles.

To obtain a measurement of use in identifying a mineral we require more than the above. Slices of a crystal of hornblende cut in various directions along the vertical axis will give different extinction-angles, from zero (straight extinction) in a section parallel to the orthopinacoid to a maximum value in a certain other section. This *maximum extinction-angle* is a character of specific value, being the angle between the vertical crystallographic axis and the nearest axis of optic elasticity. We may determine it with sufficient accuracy for most purposes by noting the extinction-angles in two or three vertical sections of the same mineral in a rock-slice and taking the largest value obtained[1].

[1] On the relation between this maximum extinction-angle and the extinction-angle measured in a cleavage-flake of hornblende or augite, see *M. M.* (1893) x, 239, 240 ; and Daly, *Proc. Amer. Acad. Arts and Sci.* (1899) xxxiv, 311—323.

By attention to the following points it is in most cases possible to refer to its crystal-system an unknown mineral of which several sections are presented in a rock-slice :

Regular system : singly refracting ; all slices extinguish completely between crossed nicols, as in glassy substances.

Tetragonal and Rhombohedral (including Hexagonal) : birefringent and uniaxial ; straight extinction for longitudinal sections of crystals with prismatic habit and for any sections of crystals with tabular habit. The two systems cannot be distinguished from one another by optical tests, but in cross-sections of prisms the crystal outline or cleavages will usually suffice to discriminate.

Rhombic (this and the remaining systems birefringent and biaxial) : straight extinction for longitudinal sections of crystals with prismatic habit; sections perpendicular to the vertical axis have axes of extinction parallel to pinacoidal faces or cleavages and bisecting the angles between the traces of prism-faces or prismatic cleavages. A section *nearly* parallel to the vertical axis will give nearly straight extinction, except in minerals which have a wide angle between the optic axes.

Monoclinic : two important types may be noticed according as the intersection of the chief cleavages (and direction of elongation of the crystals) lies in or perpendicular to the plane of symmetry. In the former case longitudinal sections may give any extinction-angle from zero up to a maximum value characteristic of the species or variety : in the latter (*e.g.* epidote and wollastonite) longitudinal sections give straight extinction. The former case is the more frequent.

Triclinic : no sections give systematically straight extinction.

Twinning. The existence of twinning in a slice of a crystal is, in general, instantly revealed by an examination of the slice between crossed nicols, since the two individuals of the twin shew different interference-tints and extinguish in different positions[1]. When twin-plane and face of association

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[1] The only exceptions (apart from opaque crystals) are in minerals, like the spinels, optically isotropic, and in cases in which the law of twinning is such that the directions of the axes of optical elasticity are not altered (*e.g.* quartz).

coincide—the most common case—a slice perpendicular to the twin-plane will give in the two individuals of the twin extinction-angles which, reckoned from the line of junction, are equal but in opposite directions. Conversely, a crystal which gives equal but opposite extinction-angles may be assumed to be cut very nearly perpendicularly to the twin-plane. If the plane of section cut the twin-plane of a crystal at a very small angle, the two individuals of the twin will overlap for a sensible width, and we shall see between the two a narrow band which does not behave optically with either.

When repeated twinning occurs, as in felspars with albite lamellation, the lamellæ divide, as regards optical behaviour, into two sets arranged alternately.

Extinction-angles in felspars. The discrimination of the several felspars by means of their extinction-angles measured on cleavage-flakes, as perfected by Schuster, is a method of great precision, but is not applicable to crystals in rock-slices. For these the method advocated by Michel Lévy and others will often be found useful. There are two cases in which it is readily applied.

(i) For crystals with albite-lamellation :—Select sections cut approximately perpendicular to the lamellæ. These are known by the extinction-angles in the two alternating sets of lamellæ, reckoned from the twin-line, being in opposite directions and nearly equal ; also by the illumination of the two sets of lamellæ being not very different when the twin-line is parallel to a cross-wire. Measure the angles in question in three or four crystals so selected, and take the greatest value found. This will be very nearly the maximum angle for all such sections, which is a specific constant for each kind of felspar, as indicated for certain types in the annexed diagram. The values for types not given in the diagram may be judged with sufficient accuracy by interpolation, since the maximum extinction-angle changes steadily from one end of the series to the other. It will be noticed, however, that in certain cases different kinds of felspar (viz. those placed on the same vertical lines in the diagram, fig. 2) give equal angles, and in this connection two remarks are to be made.

Fig. 2. Maximum extinction-angles of plagioclase felspars in
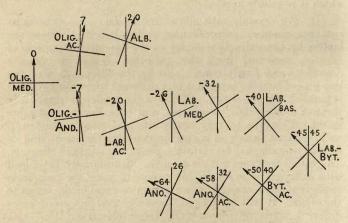sections at right angles to the albite-lamellæ.

Fig. 3. Maximum extinction-angles of plagioclase felspars in
longitudinal sections of microlites.

(*a*) A slice of a crystal has two directions of extinction, at right angles to one another. Hitherto we have taken the angle to the nearest direction of extinction, but the diagram shews that for angles of 37° or more this introduces an ambiguity. It is then necessary to distinguish between the two directions (by means of the quartz-wedge or some other contrivance) and to select that one which corresponds with the least axis of the ellipse of elasticity (indicated by an arrow-head in the diagram). In this way anorthite and bytownite are discriminated from the medium labradorites. Other criteria may sometimes be used, *e.g.* the stronger birefringence of anorthite, as pointed out below[1].

(*b*) The signs + and − denote angles measured in opposite directions crystallographically. Unless other means of discrimination can be made use of, we have usually no way of distinguishing the two directions, and there is consequently an ambiguity between albite and the more basic oligoclases (with oligoclase-andesine). Since the latter have about the same refractive index as quartz and Canada balsam, while the index for albite is distinctly lower, a discrimination may sometimes be made by rough observations of comparative refringence.

Summarily, we have the following characteristic angles for different felspars :—

    0° to 5°, oligoclase, the more acid types.
    6° to 16°, albite *and* the more basic oligoclases (with oligoclase-andesine).
  16° to 22°, andesines.
  27° to 45°, labradorites.
  45° to 50°, bytownites.
  50° and above, anorthites.

(ii) For microlites, assumed to have their length parallel to the intersection of the two principal cleavages :—Here we measure extinction-angles from the long axis of the microlites,

[1] Another point worthy of notice is the frequency with which certain angles (less than the maximum) occur in a number of sections perpendicular to the albite-lamellæ. For anorthite the favorite angles are 32° and 41°, for medium labradorite 21° and 36°.

and select the highest angle obtained by measurements on
several microlites.   The characteristic maxima for certain
varieties of plagioclase are given in the annexed diagram
(fig. 3), and the values for intermediate varieties can be
interpolated.   As before, there are two points to be noted.

(*a*)   If the angle of extinction as measured is 26° or more,
we must discriminate by the quartz-wedge or otherwise
between the two directions of extinction.

(*b*)   If the angle is 20° or less, an ambiguity occurs which
cannot be removed by this method ; viz. between albite and
andesine or andesine-labradorite and between acid oligoclase
and oligoclase-andesine.   There is thus more unavoidable
ambiguity in this case than in that of albite-lamellæ, as
appears from the following values for different felspars.

   0° to   7°, oligoclase with oligoclase-andesine.

   8° to 10°, albite-oligoclase *and* andesine.

   10° to 20°, albite *and* andesine-labradorite   with   acid
          labradorite.

   30° to 42°, labradorite, medium to basic.

   49° to 56°, bytownites.

   58° to 64°, anorthites.

Becker[1] has suggested another test applicable to microlites,
which may very conveniently be used to supplement the above ;
since, although it is of little use for the more basic varieties,
it affords a useful criterion for distinguishing the oligoclases,
andesines, *etc.*   Instead of longitudinal sections, perpendicular
cross-sections of the microlites are selected.   These are small,
nearly square, and sharply defined.   The extinction-angles
vary from −13° for pure albite to 42$\frac{1}{2}$° for anorthite, and from
Becker's figures we may deduce the following approximate
values :—

[1] 18*th Ann. Rep. U. S. Geol. Sur.* (1898) part III, 32—34, and *A. J. S.*
(1898) v, 349—354, pl. III.   For a more general account of the modern
optical methods of discriminating the felspars see Winchell, *Amer. Geol.*
(1898) xxi, 12—48, pl. II—VIII.

    0° to   4°, oligoclase, acid.
    4° to   7°, oligoclase, medium, *and* albite-oligoclase.
    7° to 13°, oligoclase, basic, *and* albite.
  18° to 22°, andesine.
26½° to 38°, labradorite, acid to medium.
38° to 42½°, medium labradorite to anorthite.

If the sections selected for measurement be as much as 10° from the true perpendicular cross-section, the resulting error is only about 1½° to 2½° in the more acid half of the plagioclase series, and therefore does not vitiate the conclusion.

Zonary banding in felspars. In many rocks the felspars shew between crossed nicols concentric zones roughly parallel to the boundary of the crystal, the successive zones extinguishing in different positions. (If there be albite-lamellation, we confine our attention to one of the two sets of lamellæ.) This difference in optical behaviour among the successive layers which build up the crystal may arise in two ways : firstly, from the successive zones being of different kinds of felspar-substance ; or, secondly, from ultra-microscopic twinning affecting in various degrees the different layers of a crystal chemically homogeneous. This has been pointed out by Michel Lévy, and he gives a test which will resolve all except certain rare cases. It will be found, on rotating the slice between crossed nicols, that there are certain positions in which the albite-lamellæ disappear. If simultaneously with this the zonary banding disappears also, so that the whole crystal[1] is uniformly illuminated, the appearances can be explained by ultra-microscopic twinning alone : if this is not the case, the zonary banding may be ascribed to the successive layers of felspar-substance in each crystal differing in chemical composition. When this occurs, the rule generally holds that the layers or zones become progressively more acid from the centre to the margin.

Interference-tints. We have remarked that a thin slice of a doubly refracting crystal, examined between crossed nicols, is in general not dark except when placed in certain

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[1] Or if there be Carlsbad twinning also, the whole of one individual of the Carlsbad twin.

definite positions. In any other position it does not completely
extinguish the light, but its effect, in conjunction with the
nicols, is partially to suppress the several components of the
white light in different degrees, so that in the emergent beam
these components are no longer in the proportions to give white
light. In this way arise polarization-tints or interference-tints.
These belong to a definite scale, known as *Newton's scale*, on
which the several tints (though graduating into one another)
are distinguished by names and divided into several 'orders.'
The student should learn the succession of these tints, in the
first place from the coloured plates accompanying some mineral-
ogical works[1], but ultimately from the minerals themselves.
The precise position in the scale of a given tint observed
between crossed nicols can be fixed by means of a quartz-
wedge or other contrivance for 'compensating' or neutralising
the birefringence of the slice ; but for ordinary purposes, at
least with colourless or nearly colourless minerals, the inter-
ference-tint can be judged by eye with sufficient accuracy.
The most brilliant colours are those of the second order and
at the top of the first ; the lowest colours of the first order are
dull greys ; while in the third and fourth orders the tints
become brighter but paler, ultimately approximating to white.

The interference-tints given by a crystal-section depend
(i) on the birefringence of the mineral, which is a specific
character ; (ii) on the direction of the section relatively to the
ellipsoid of optic elasticity, the tint being highest for a section
parallel to the greatest and least axes of the ellipsoid ; (iii) on
the thickness of the slice. These last two are disturbing
factors, which must be eliminated before we can use the inter-
ference-tints as an index of the birefringence of the crystal,
and so as a useful criterion in identifying the mineral.

The fact that the interference-tints depend in part on the
direction of the section through the crystal will rarely be
found to give rise to any difficulty in estimating roughly the
birefringence of the mineral. If two or three crystals of the
same mineral are contained in a rock-slice, it is sufficient to

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[1] Michel Lévy and Lacroix, *Les Minéraux des Roches* : Rosenbusch
(transl. Iddings), *Microscopical Physiography of the Rock-making
Minerals.*

have regard to that one which gives the highest interference-tints. Even a single crystal will in the majority of cases give tints not so far below those proper to the mineral as to occasion error, but the possibility of the section having an unlucky direction must be borne in mind.

Rock-slices prepared by a skilful operator are in most cases so nearly constant in thickness that variations in this respect may be left out of consideration. Any important difference is at once detected by well-known minerals giving unusual interference-tints. Thus if quartz or orthoclase give the yellow of the first order, the slice is rather a thick one; if they give orange or red, the slice is considerably thicker than the average of good preparations. Knowing this, we can make allowance for it in estimating the birefringence of some doubtful mineral in the same slice. Such allowance can be roughly judged, or it can be made with considerable precision by means of the large coloured plate of Michel Lévy and Lacroix[1].

The actual birefringence (numerically expressed) of the several rock-forming minerals, and the interference-tints which they afford in slices of ordinary thickness, are given in numerous books and tables. For rough purposes the student will find it useful to remember about as much as is contained in the following table.

Birefringence and interference-tints of the commoner rock-forming minerals. (The colours given are for slices ·001 inch in thickness.)

Very weak (giving steel-grey tints): leucite, apatite, nepheline, melilite.

Weak (giving blue-grey to white of first order): zoisite, microcline, orthoclase, albite, oligoclase, andesine, labradorite, quartz, bytownite, enstatite.

Moderate (giving white, yellow, or orange of first order): andalusite, chlorite, anorthite, hypersthene.

Strong (giving red of first order to violet and blue of second): tourmaline, augite and diallage, common hornblende and actinolite.

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[1] This plate can be purchased separately and mounted as a wall-diagram. On the method of using it see Pirsson and Robinson, *A. J. S.* (1900) x, 260—265.

Very strong (giving green, yellow, or orange of second order) : olivine, epidote, talc, biotite, muscovite.

Extremely strong (giving the pale colours of the third and fourth orders to almost pure white) : zircon, hornblende rich in iron, sphene, calcite and dolomite, rutile.

Note that in minerals with strong absorption, such as the deep-coloured micas and hornblendes, the interference-colours are more or less masked by those due to absorption.

Pleochroism. A character often useful in identifying minerals is pleochroism, the property of giving different absorption-tints for different directions of vibration of the light within the crystal. To observe this property, we use the lower nicol only, and rotate either it or the stage. The direction of vibration is that of the shorter diagonal of the nicol.

It is necessary not only to observe the changes of colour, if any, but also to note their relation to directions of vibration within the crystal. For example, elongated sections of biotite and hornblende, tourmaline and sphene, may be found to change from a deeper to a paler tint of brown on rotation ; but while in the first pair of minerals the direction of vibration most nearly coincident with the long axis of the section gives the deeper tone, in the second pair it gives the paler.

To be more precise, we wish to know, for a specification of the pleochroism of a given mineral, the absorption-tints for vibrations in three definite directions within the crystal—those of the three axes of optical elasticity. Taking a given mineral, say a hornblende, of which a number of crystals occur in our slice, we may proceed as follows. Select a crystal shewing only one set of cleavage-traces and giving the maximum extinction-angle : this section will be approximately parallel to the plane of symmetry, which contains two of the required axes. These axes are the axes of extinction for the section, and their positions are thus easily found. The one nearest to the cleavage-traces is the γ-axis, the other the α-axis. Bring the γ-axis to coincide in direction with the shorter diagonal of the nicol, adjusting the position by obtaining extinction, and then removing the upper nicol. Observe the colour : then do the same for the α-axis. For the remaining β-axis we must

use another crystal. We may choose one shewing only a single set of cleavage-traces and giving straight extinction : the β-axis is perpendicular to the cleavage-traces. Or we may choose a section shewing two sets of cleavage-traces intersecting at a good angle and extinguishing along the bisectors of the angles between the cleavage-traces : the β-axis is the bisector of the acute angle.

Minerals of the rhombohedral and tetragonal systems can have only two distinct absorption-tints (*dichroism*), one for vibrations parallel to the longitudinal axis (extraordinary ray), the other for vibrations in any direction perpendicular to it (ordinary ray). In the regular system the absorption-colours are independent of direction.

In consequence of pleochroism the absorption-tints of a mineral vary in differently cut crystals seen in natural light, but the precise nature of the pleochroism can be investigated only with a polarized beam.

Examination of a rock-slice. In studying a rock-slice it is always well to proceed methodically. A low power should first be used : any object which it is desirable to examine under a higher magnification should be brought to the centre of the field before the objective is changed for a higher power. The slice should always be observed first in natural light : by their outline, relief, cleavages, inclusions, alteration-products, *etc.*, all the ordinary rock-forming minerals can be identified in most cases without the use of polarized light. If the lower nicol is not readily movable it may be left in for many purposes, but it must be remembered that half the illumination is thus cut off, and for any but the lowest magnifying powers this is of importance. Opaque substances should always be viewed in reflected light.

To examine the pleochroism of any coloured constituent, we put in the lower nicol, and rotate either it or the stage. For verifying feeble pleochroism the former plan is preferable, but the nicol must be rotated until its catch holds it before proceeding to the use of the two nicols, which will be the next act.

For some purposes oblique illumination is advantageous. For instance, the extremely slender needles of apatite in

certain lamprophyres and other rocks become visible only by this means. A 'spot-lens' may be improvised by placing beneath the stage a convex lens of short focal length with its central part covered by a disc of black paper.

In using a high power it will be noticed that the focus is very perceptibly different for the upper and lower surfaces of the slice. To make out the form of a body enclosed in the thickness of the slice the focus should be gradually moved, so as to bring different depths successively into view.

It cannot be too strongly insisted that the identification of the component minerals of a rock is only a part of the examination. The mutual relations of the minerals and their structural peculiarities must also be observed, the order of crystallization, intergrowths, interpositions, decomposition-products, pseudomorphs, *etc.*, as well as special rock-structures such as fluxion-phenomena, vesicles, effects of strain and fracture, *etc.* In short, the object of investigation should be not merely the composition of the rock, but its history.

Classification and nomenclature of rocks. Petrology has not yet arrived at any philosophical classification of rocks. Further, it is easy to see that no classification can be framed which shall possess the definiteness and precision found in some other branches of science. The mathematically exact laws of chemistry and physics which give individuality to mineral species do not help us in dealing with complex mineral aggregates; and any such fundamental principle as that of descent, which underlies classification in the organic world, has yet to be found in petrology. Rocks of different types are often connected by insensible gradations, so that any artificial classification with sharp divisional lines cannot truly represent the facts of nature. At present, therefore, the best arrangement is that which brings together as far as possible, for convenience of description, rocks which have characters in common, the characters to be first kept in view being those which depend most directly upon important genetic conditions. The grouping adopted below must be regarded as one of convenience rather than of principle.

In a perfect system the nomenclature should correspond with the classification. This is of course impossible at present

in petrology. Moreover great confusion has arisen in the nomenclature of rocks in consequence of the rapid growth of descriptive petrography. Many of the names still in use are older than the modern methods of investigation : they were given at a time when trivial distinctions were emphasized, while rocks essentially different were often classed together. Later writers, each in his own way, have arbitrarily extended, restricted, or changed the application of these older names, besides introducing new ones. The newer rock-names need cause no confusion, provided they are employed in a strict sense. Thus 'foyaite' should be used for rocks like that of Foya, specimens of which are in every geological museum : to extend the name to all nepheline-bearing syenites is to introduce needless ambiguity. In practice perhaps the most convenient usage is to speak of 'the Foya type,' 'the Ditro type,' *etc.*, referring in each case to a described and well-known rock. There remain the names employed for families of rocks : some of these are old names, such as granite and syenite, which have come to have a tolerably well understood signification, not always that first attached to them ; others, such as peridotite, have been introduced to cover rocks not recognized as distinct families by the earlier geologists. A division of a family is often designated by prefixing the name of some characteristic mineral of that division ; *e.g.* hornblende-granite, hypersthene-andesite, *etc.*

These remarks apply more especially to igneous rocks, which we shall consider first. Such rocks, formed by the consolidation of molten 'magmas,' differ from one another in character, the differences depending partly on the composition of the magma in each case, partly on the conditions attending its consolidation. The composition is to some extent indicated by the essential minerals of the rock, which thus become an important, though not logically a prime, factor in any genetic classification. It is evident, however, that a mere enumeration of the minerals of a rock, without taking account of their relative abundance, cannot give a very precise idea of the bulk-analysis[1]; while, on the other hand, it appears on examination that magmas of very similar composition may, under

[1] This difficulty is only partially evaded by ranking some of the constituent minerals as *essential* and others as *accessory*.

different conditions of consolidation, give rise to widely different mineral-aggregates. Again, many rocks consist only in part of definite minerals, the residue being of unindividualised matter or 'glass.'

To diverse conditions of consolidation must be referred differences in coarseness or fineness of texture, the presence or absence of any glassy residue, the evidence of one or more than one distinct stage in the solidification, and, in general, the peculiarities in the mutual arrangement of the constituent minerals, which collectively are termed the 'structure' of the rock.

The massive igneous rocks will first be divided into three groups: abyssal or *plutonic, hypabyssal,* and superficial or *volcanic.* These names express the different geological relations of the several groups as typically developed, but the divisions themselves are based upon the characteristic structural features which different conditions of consolidation have impressed upon the rocks. Under each of these three heads the various rock-types will be grouped in families founded proximately on the mineralogical, ultimately on the chemical, composition, though this cannot be done without some few inconsistencies. The families will be arranged roughly in order from the more acid to the more basic, but it must be remembered that such an arrangement in linear series can represent only very imperfectly the manifold diversity met with among igneous rocks.

A. PLUTONIC ROCKS.

THE rock-types to be treated under the head of plutonic or abyssal are met with, in general, in large rock-masses which have evidently consolidated at considerable depths within the earth's crust. Transgressive as regards their actual upper boundary, their geological relations on a large scale are, as a rule, only imperfectly revealed by erosion; so that their actual form and extent are often matters of conjecture. Some of the masses seem to be of the nature of great laccolites; others have been supposed to mark reservoirs of molten magma, which once furnished the material of minor intrusions and surface volcanic ejectamenta. The immediate apophyses of the large masses have similar petrographical characters.

The distinctive features of these rocks of deep-seated consolidation are those which point to slow cooling (not necessarily slow consolidation) and great pressure. The rocks are without exception *holocrystalline, i.e.* they consist wholly of crystallized minerals with no glass. Even as microscopic inclusions in the crystals, glass is much less characteristic than water, which gives evidence of high pressure during the crystallization. The texture of plutonic rocks may be comparatively coarse, *i.e.* the individual crystals of the essential minerals may attain considerable dimensions. The typical structure is that known as *hypidiomorphic,* only a minor proportion of the crystals being 'idiomorphic' (*i.e.* developing their external forms freely), while the majority, owing to mutual interference, are more or less 'allotriomorphic' (taking their shape from their surroundings)[1]. It should be observed that a crystal may be strictly idiomorphic without having any regular crystal-outlines : this is often the case with olivine[2].

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[1] This is the terminology used by Rosenbusch. Zirkel has adopted Rohrbach's terms *automorphic* and *xenomorphic* in the same senses.

[2] Pirsson has suggested the term *anhedron* (with adjective *anhedral*) for a crystal not possessing external crystal-faces : *Bull. Geol. Soc. Amer.* (1895) vii, 492.

Sequence of crystallization. The terms just intro-
duced are used with a relative signification ; so that a given
mineral in a rock may be allotriomorphic towards certain
associated minerals and idiomorphic towards others. By
observing such points we are able to make out the order in
which the several minerals composing an igneous rock have
crystallized out from the parent rock-magma. It is found that
there exists in plutonic rocks a normal order of consolidation
for the several constituents, which holds good with a high
degree of generality. It is in the main, as pointed out by
Rosenbusch, a law of ' decreasing basicity.' The order is
briefly as follows.

I.   Minor accessories (apatite, zircon, sphene, garnet, *etc.*)
        and iron-ores.

II.   Ferro-magnesian minerals :—olivine, rhombic pyroxenes,
        augite, ægirine, hornblende, biotite, muscovite.

III.   Felspathic minerals :—plagioclase felspars (in order from
        anorthite to albite), orthoclase (and anorthoclase).

IV.   Quartz, and finally microcline.

In most rocks such minerals as are present follow the
above order. The most important exceptions are the inter-
growth of orthoclase and quartz and the crystallization of
quartz in advance of orthoclase in some acid rocks, and the
rather variable relations between groups II. and III. in some
more basic rocks. The order laid down applies in general to
parallel intergrowths of allied minerals : thus when augite is
intergrown with ægirine or hornblende, the former mineral
forms the kernel of the complex crystal and the latter the
outer shell ; when a plagioclase crystal consists of successive
layers of different compositions, the layers become progressively
more acid from the centre to the margin.

Certain constituents having variable relations are omitted
from the foregoing list. Thus nepheline (elæolite) and sodalite
belong to group III., but may crystallize out either before or
after the felspars.

Varieties of structure in plutonic rocks. The
typical structure of rocks of plutonic habit is that implied
in the foregoing remarks, and is known as the *granitoid* or

eugranitic structure[1]. Among the more special modifications frequently met with are those depending upon the simultaneous crystallization of two of the essential minerals, giving rise to the so-called 'graphic' intergrowths, usually on a microscopic scale. The resulting *micrographic,* micropegmatitic or granophyric structure is most common in the quartz-bearing rocks, and arises there from an intimate interpenetration of part of the felspar by quartz (fig. 7, *A*). Within a certain area of a slice the quartz of such an intergrowth behaves optically as if it were a single crystal, the whole becoming dark between crossed nicols in one position. On rotation the felspar can be made to extinguish in its turn. Intergrowths of other minerals (*e.g.* augite and felspar) are less common. In both granitoid and micrographic rocks there sometimes occur vacant interstitial spaces or little cavities of irregular shape, into which project the sharp angles of well-formed crystals. Such rocks are said to have a *miarolitic* or drusy structure, but this peculiarity is often obscured by secondary products occupying the druses.

Opposed to the granitoid is the *granulitic* structure. In this a section of the rock appears as a mosaic of roughly equidimensional grains, usually of small size. There is only in some cases a tendency to crystallographic development (panidiomorphic structure) or again the earlier-formed minerals tend to take on rounded outlines. The structure probably results from movement during the process of consolidation, and we shall see that very similar appearances may be produced by the deformation and crushing of already solidified granitoid rock-masses.

Both granitoid and granulitic rocks sometimes exhibit in greater or less degree a parallel disposition of elongated or tabular crystals of felspar, mica, *etc.*, indicative of some flowing movement of the rock-magma subsequently to the separation of those crystals. With this there may be a certain banding of the rock due to alternations of slightly different types (mineralogically or structurally), which is known as a *gneissic* structure. These characters, however,

[1] The term 'granolite,' applied to such rocks by some American writers, is ill chosen, as likely to be confused with 'granulite.'

may also have a quite different and secondary origin, and we shall defer notice of them to another place (Chap. XXII.).

Traversing plutonic rock-masses of normal structural types, or bordering them as an irregular fringe, may often be found strikingly coarse-textured or *pegmatitic* modifications, with a strong tendency to graphic intergrowths[1]. While clearly related to the associated plutonic rock-masses, these pegmatitic rocks differ from them mineralogically in the sense of being somewhat more acid, and they are further characterized by the frequent occurrence of special minerals, often including compounds of the rarer chemical elements. They are usually regarded as representing the final (pneumatolytic) phase of consolidation of the rock-magmas from which they were formed[2]. The lighter-coloured veins and streaks often seen traversing plutonic rocks are in many respects comparable with the pegmatites. They invariably shew a coarser texture and a more acid composition than the main mass in which they occur ; and, though they more or less clearly cut the latter, the relations are such as to prove that their origin is bound up with that of the main rock-mass. They are sometimes spoken of as (relatively) *acid excretions* from the crystallizing magma.

Contrasted with these, there occur in many plutonic rocks darker and finer-textured ovoid or irregularly rounded patches which are usually considered as (relatively) *basic secretions* from the magma, belonging to an early stage in the history of consolidation. Composed in general of the same minerals as the enclosing rock, they are richer in the earlier-formed— which are also the denser and more basic—constituents. The lighter-coloured veins, on the other hand, are relatively rich in the later-formed and more acid minerals.

The typical plutonic rocks are *non-porphyritic, i.e.* there is evidence of but one continuous stage in the consolidation. In many hypabyssal and almost all volcanic rocks, some one,

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[1] The original pegmatite of Haüy was such an intergrowth of quartz and felspar ('graphic granite'), but the modern usage of the name is more extended.

[2] On this point see G. H. Williams, 15th *Ann. Rep. U. S. Geol. Sur.* (1895) 675—684.

or more, constituent (usually a felspar) occurs in two distinct generations with different habits and characters, belonging to an earlier and a later stage of consolidation, in which quite different conditions prevailed. This is the 'porphyritic' structure, and is typically wanting among plutonic rocks, which have what has been termed an 'even-grained' character ('körnig' of Rosenbusch). In some of the plutonic rocks, however, and especially among the granites, occur relatively large crystals of felspar, which give a *porphyritic* character to the rock of which they form part, and perhaps point to different conditions from those under which the main mass of the rock consolidated; but even here there is no sharp division between an earlier and a later period of crystallization, such as is indicated in the volcanic rocks [1].

We shall consider the several families in an order which corresponds roughly with their chemical relationship, beginning with the acid rocks and ending with the ultrabasic.

[1] *Cf.* Lawson on the Santa Lucia granite in California, *Bull. Dep. Geol. Univ. Cal.* (1893) i, 9—15.

CHAPTER II.

GRANITES.

The granites are even-grained holocrystalline rocks composed of one or more alkali-felspars, quartz, and some ferro-magnesian mineral, besides accessory constituents. The rocks are generally of medium to rather coarse grain, and the tendency of the crystals as a whole to interfere with one another's free development gives what Rosenbusch styles the hypidiomorphic structure.

According to their characteristic minerals, after felspars and quartz, the rocks are described as *muscovite-*, *biotite-*, *hornblende-*, and *augite-granites;* and this division corresponds roughly with different chemical compositions, from more to less acid types. *Tourmaline-granite* must be considered a special modification of the above, and, in particular, of the more acid kinds. With the granites we shall also include certain rocks (*aplite, pegmatite, greisen*) associated with granites but differing from them in important structural and mineralogical characters, some of them never forming, like the true granites, large bodies of rock.

Constituent minerals. Felspars make up the greater part of a granite, a potash- and a soda-bearing felspar commonly occurring together. The potash-felspar is often *orthoclase*, either in simple crystals or in Carlsbad twins, the Baveno twin being uncommon[1]. When fresh, it shews its cleavages and sometimes a slight zonary banding, but these appearances are lost when the mineral is altered to any extent. The

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[1] Cohen (3), pl. xxiv, fig. 2; Rosenbusch-Iddings, pl. xxiii, fig. 3.

common decomposition-processes give rise either to finely
divided kaolin or to minute flakes of mica. When the latter
are large enough to be clearly distinguished, they are often
seen to lie along the cleavage-planes of the felspar. Decom-
position often begins in the interior of a crystal, which may
be clouded or completely obscured while the margin remains
clear. Instead of orthoclase we often find *microcline*, which
is usually the last product of consolidation in the rock. When
fresh, microcline shews its characteristic 'cross-hatched' struc-
ture[1] and sometimes a vein-like intergrowth of albite[2] (fig. 4).
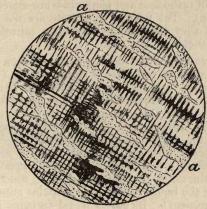
Fig. 4. Microcline from the 'rapakiwi' granite of Finland ; × 20.
    Crossed nicols : shewing the characteristic 'cross-hatching.' It is
traversed by veinlets of albite (*a*) intergrown with crystallographic
relation to the microcline [1031].

Some petrologists hold that the peculiar microcline-structure,
due to fine twin-lamellation in two directions, is not essential,
and may be set up in some cases as a secondary effect of
strain ; and that the quasi-monoclinic mineral orthoclase is
merely microcline in which the twin-lamellation is carried to
an ultra-microscopic degree of fineness[3]. The alteration of

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[1] Cohen (3), pl. xxviii, figs. 1, 2 ; pl. xxxii, fig. 4.
[2] Rosenbusch-Iddings, pl. xxv, fig. 1.
[3] *Cf.* Teall, *Ann. Rep. Geol. Sur.* for 1895, p. 24 ; Keyes, 15*th Ann.*
Rep. U. S. Geol. Sur. (1895) 711, 712.

microcline by weathering is similar to that of orthoclase. The soda-felspar of most granites ranges from *albite* to *oligoclase*. It has rather a tabular habit, giving rise to elongated rectangular sections. It is always twinned on the albite- and occasionally too on the pericline-law. The common decomposition-products are kaolin, sometimes paragonite mica, and in the lime-bearing varieties some epidote or calcite. The most typical 'soda-granites' contain albite to the exclusion of potash-felspars, but this is an exceptional type (Croghan Kinshela in Wexford, Mariposa in the Sierra Nevada). Parallel intergrowths of orthoclase and plagioclase are sometimes found (microperthite). The felspars of granite are not rich in inclusions, but they may inclose sparingly microlites of the earlier constituents of the rock.

The *quartz* of granites does not usually shew any crystal boundaries, except on the walls of drusy cavities ('miarolitic' structure), or less perfectly when the mineral is enclosed by microcline. Its most characteristic inclusions are fluid-cavities (fig. 1, *b—e*): these are sometimes in the form of 'negative crystals,' either dihexahedral pyramids or elongated prisms; more usually the shape is rounded or irregular. These fluid-pores often occur with a definite arrangement along certain planes, appearing in a section as lines[1]. The enclosed liquid does not fill the cavity, but leaves a bubble, which is mobile. In some cases the liquid is brine, and contains minute cubes of rock-salt (Dartmoor). In others liquid carbonic acid occurs instead of, or in addition to, water, and in some cases we see one bubble within another[2]. Glass- and stone-cavities are less abundant. Sometimes extremely fine needles are enclosed (Peterhead): these seem to be rutile, and sometimes shew the characteristic knee-shaped twin.

The dark micas of granites are usually termed *biotite.* This may be considered to include varieties rich in ferrous oxide (the haughtonite of many Scottish and Irish granites), or in ferric oxide (lepidomelane). The mineral builds roughly hexagonal plates, which, cut across, give an elongated section shewing the strong basal cleavage[3]. A lamellar twinning

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[1] Cohen (3), pl. xi, fig. 1.   [2] *Ibid.* pl. xii, fig. 3.
[3] *Ibid.* pl. xl, fig. 2.

parallel to the base is probably common, but, owing to the nearly straight extinction, this is not often conspicuous. The fresh biotite is deep brown with intense pleochroism. Its common inclusions are apatite, zircon, and magnetite, and the minute zircons are always surrounded by a 'halo' of extremely deep colour and intense pleochroism[1] (Skiddaw, Dartmoor, Dublin, *etc.*). Decomposition often produces a green coloration[2] and ultimately a green chloritic pseudomorph with secondary magnetite-dust. This magnetite may be reabsorbed, restoring the brown colour but with less pleochroism and with loss of cleavage.
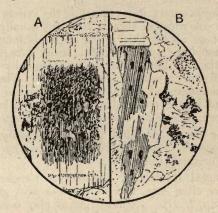
Fig. 5. Granite, near Dublin; × 20.

A. Crystal of oligoclase shewing zonary structure and decomposition beginning in the interior [389]. *B.* Parallel intergrowth of biotite and muscovite [1774].

The colourless, brilliantly-polarizing *muscovite* forms rather ragged flakes, posterior to the biotite or partly in parallel intergrowth[3] with it (Dublin, *etc.*, fig. 5, *B*). It is always clear, and is not susceptible to weathering. A lithia-mica, in large

[1] Cohen (3), pl. LIV, figs. 3, 4. [2] *Ibid.* pl. LVII.
[3] *Ibid.* pl. XXXII, fig. 2.

flakes, takes the place of muscovite in some greisens and peg-
matites.

The crystals of *hornblende* are irregularly bounded, or at
least without terminal planes. They shew the prismatic
cleavage, and occasionally lamellar twinning parallel to the
orthopinacoid. The colour is green or brownish-green, with
marked pleochroism, and the extinction-angle in longitudinal
sections always low. Besides inclusions of earlier minerals,
there may be an intergrowth with biotite. The common
decomposition-products are a green chloritic substance or an
epidote and quartz.

When *augite* occurs, it is commonly the variety malacolite
or diopside, colourless in slices. It is not usually in perfect
crystals, but an idiomorphic green augite is found in some
coarsely granophyric types of rock (Mull). Augite may be
either uralitized or decomposed into a green chloritic mineral
or into a mixture of serpentine and calcite. The augite is
sometimes accompanied by a rhombic pyroxene (enstatite,
Cheviot), and in one remarkable group of granitic rocks the
dominant ferro-magnesian element is *hypersthene*.

Iron-ores are not plentiful in granites. *Magnetite* may
occur or *hæmatite*, either opaque or deep-red ; *pyrites* is also
found as an original mineral.

Acute-angled crystals of light-brown pleochroic *sphene*
(titanite) are often seen, and in the less acid granites are
abundant (fig. 7, *B*). Rounded grains may occur instead.
The high refractive index and other optical properties enable
the mineral to be readily identified. The little prisms of
zircon[1] are even more highly refractive (fig. 1, *k*), but when
they occur, as they often do, enclosed in the biotite, the
pleochroic halo is liable to obscure their nature. *Apatite*
builds narrow colourless prisms, and often penetrates the
biotite. Small reddish *garnets* occur in some muscovite-
granites and aplites (Dublin) : other unusual minerals are
cordierite, usually pseudomorphed by the micaceous substance
termed pinite, and *andalusite*, coated with flakes of muscovite.
In some granites from America and elsewhere *allanite* (orthite)

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[1] Cohen (3), pl. III, fig. 3.

is found[1], while others contain epidote, often with an intergrown core of allanite[2]. Though epidote is a well-known weathering-product in granitic rocks, this relation to allanite and the occasional inclusion of good crystals of epidote in flakes of biotite seem to point to its primary origin in these cases[3].

Tourmaline characterizes a common modification of granite, especially near the margin of a mass. It may be in good crystals but more frequently has ragged outlines. The rude
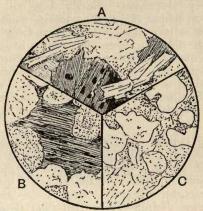

FIG. 6. REVERSALS OF NORMAL ORDER OF CRYSTALLIZATION IN
GRANITES ; × 20.

A. Biotite moulded on muscovite, Rubislaw, Aberdeen [390 *a*].
B. Biotite moulded on quartz and felspars, Meillionydd, near Sarn, Caernarvonshire [814]. *C.* Orthoclase moulded on quartz, Shap [892].

cross-fracture is often apparent. The colour is brown, sometimes with patches of blue[4], and the dichroism is strong, the

[1] Iddings and Cross, *A. J. S.* (1885) xxx, 108–111; McMahon, *G. M.* 1899, 194–196 (Lairg).
[2] Hobbs, *A. J. S.* (1889) xxxviii, 223–228 ; *Amer. Geol.* (1893) xii, 218, 219.
[3] Hobbs, *Amer. Geol.* (1893) xii, 218, 219; Keyes, *Bull. Geol. Soc. Amer.* (1893) vi, 305–312; 15*th Ann. Rep. U. S. Geol. Sur.* (1895) 704–710, pl. xxxviii, figs. 1–4, xxxix, figs. 1–3, xl.
[4] Cohen (3), pl. xxii, fig. 2.

strongest absorption being for vibrations transverse to the long axis (the 'ordinary' ray).

Structure. In the granites the normal order of crystallization of the constituent minerals rules with few exceptions. The minor accessory minerals crystallized out first, and are thoroughly idiomorphic, *i.e.* have taken their shape without external interference. The ferro-magnesian minerals have in general preceded the felspars, being often embraced or even enclosed by them, though the felspars also may tend to take on partial crystal-outlines. Rarely does, *e.g.*, mica occur interstitially to felspar (fig. 6, *B*). Biotite moulded on muscovite is not so rare (fig. 6, *A*). Apart from micrographic structures, the felspars, except microcline, have crystallized prior to the quartz, exceptions being infrequent (fig. 6, *C*). Where micrographic intergrowths occur, the felspar may be either orthoclase or a plagioclase (fig. 7, *A*). We need not further specify other structural peculiarities such as the miarolitic, the porphyritic, the gneissic, and the spheroidal or orbicular[1].

Leading types. Almost all the true granites contain a brown mica. If a white mica be present in addition, we have *muscovite-granite* ('two-mica granite' or 'granite proper' of the Germans, 'granulite' of the French[2], 'binary granite' of some American writers[3]). Such rocks are commonly somewhat more acid in composition than those with dark mica only. The Carboniferous granites of Cornwall and Devon afford good examples. They consist of orthoclase, a plagioclase, quartz, and two micas[4], with the normal order of crystallization. The quartz has fluid-cavities, often enclosing

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[1] Hatch, *Q. J. G. S.* (1888) xliv, 548–559, pl. xiv (Mullaghderg in Donegal), with a summary of information on spheroidal granites in general; Turner, *Journ. Geol.* (1899) vii, 154 (Bridal Veil in Yosemite Park); Harris, *G. M.* 1898, 11–13 ('Rapakiwi' granite of Finland).

[2] The granulite of German and English petrologists has a different signification.

[3] This term, however, has also been applied to rocks consisting essentially of felspar and quartz, without mica.

[4] Dr Haughton's analyses of the Trewavas Head rock proved the felspar to be albite, the dark mica lepidomelane, and the white mica lepidolite; *Q. J. G. S.* (1869) xxv, 166, 167.

minute cubes of rock-salt[1] (Dartmoor, fig. 1, c). Parallel intergrowths of biotite and muscovite are common. The minor constituents of the rock are magnetite, apatite, and zircon, the last, when it is enclosed in the biotite, being always encircled by the characteristic halo of intense pleochroism. More exceptional accessory minerals are andalusite, in pleochroic crystals coated by flakes of muscovite (Cheesewring), and 'pinite' pseudomorphs after cordierite (Land's End). Tourmaline is common, and the rocks graduate into tourmaline-granites, especially near the margin of an intrusion.

The post-Ordovician granites which occupy so large a tract in Leinster[2] (e.g. Dalkey near Dublin) are of a different type. They also have two micas, often in parallel intergrowth, and apatite and zircon are characteristic accessories; but the potash-felspar is microcline[3], and is the latest product of crystallization. A plagioclase felspar is plentiful, and exceptionally albite is the only felspathic element present (Croghan Kinshela in Wexford). Little crystals of garnet occur in some instances (Three Rock Mountain near Dublin). This mineral is found also in the granite of Foxdale in the Isle of Man[4], a closely similar rock, in which the dark mica is very subordinate to the white. Another well-known microcline-bearing rock is the 'grey Aberdeen granite' of Rubislaw, etc. Similar rocks are found in Donegal.

Among American muscovite-granites may be mentioned those of Concord and Haberville, N.H., and the porphyritic granite of Coanicut Island, R.I.[5] Others occur in Maine, Vermont, and Connecticut.

Rocks in which muscovite is only sparingly or occasionally present form a link with the next division. The Skiddaw granite is of this character[6]. Here the quartz is in great part of prior crystallization to the orthoclase, or there may be

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[1] Hunt, G. M. 1894, 102–104, with figures.
[2] Sollas, Trans. Roy. Ir. Acad. (1891) xxix, 427–512; Pr. Geol. Ass. (1893) xiii, 106; Watts, Guide, 31–33.
[3] O'Reilly, Sci. Pr. Roy. Dub. Soc. (1879) ii, 246–248, pl. xv.
[4] Naturalist, 1894, 68; Q. J. G. S. (1895) li, 143.
[5] Pirsson, A. J. S. (1893) xlvi, 372, 373.
[6] Q. J. G. S. (1895) li, 140.

some micrographic intergrowth of the two minerals. Felspar-quartz-rocks free from mica are found among the pre-Cambrian intrusions of Ercal in the Wrekin district and of the Malverns. Here too the quartz has crystallized, or has finished crystallizing, before the dominant felspar, which is often microcline. These rocks seem to have affinities with the pegmatites.

The commonest division of the granite family is perhaps *biotite-granite* (Fr. granite, Ger. Granitit), characterized by containing a brown mica to the exclusion of muscovite, hornblende, or augite. Such a rock may consist, *e.g.*, of orthoclase, albite or oligoclase, quartz, biotite, and minor accessories, with the normal order of crystallization.

The relative proportions of the several minerals vary considerably. In the granites (Ordovician and perhaps some
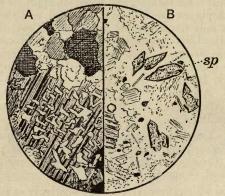
Fig. 7; ×20.

A. Micrographic intergrowth of plagioclase felspar and quartz in granite, St David's; crossed nicols [293]. B. Crystals of sphene (*sp*) in dark basic secretion in Shap granite, Westmorland [1070].

older) of Wales[1] quartz is very abundant, and biotite (often chloritized) is only sparingly found. The dominant felspar

[1] *Q. J. G. S.* (1888) xliv, 444, 445, and *Bala Volc. Ser. Caern.* 59, 61 (Sarn); Geikie, *Q. J. G. S.* (1883) xxxix, 314, pl. x, fig. 11 (St David's); Jennings and Williams, *ibid.* (1891) xlvii, 380 (Ffestiniog).

is often a plagioclase (Caernarvon, St David's, *etc.*), and probably some of these rocks would be placed among the 'soda-granites' of certain authors. The St David's rock shews a strong tendency to the micrographic structure (fig. 7, *A*).

In the biotite-granite of Eskdale, Cumberland, the quartz is either intergrown in micrographic fashion with the ortho-clase, or has crystallized before it. The latter is the case too in the well-known porphyritic granite of Shap in Westmor-land[1] (fig. 6, *C*), which is further noteworthy for its abundant sphene. Both micrographic and miarolitic structures charac-terize the Tertiary biotite-granites of the Mourne Mts, Carlingford[2], and Arran, the crystals on the walls of the druses presenting very perfect crystal boundaries.

Biotite-granites are extensively developed in the Cairngorm[3] and Monadhliath Mts and other parts of the Scottish High-lands. In many British examples microcline partly or wholly takes the place of orthoclase (Malvern, Ross of Mull, Peter-head, *etc.*). Albite-veins intergrown in both orthoclase and microcline may sometimes be observed, *e.g.* in the Eskdale rock already alluded to.

Biotite-granites are of wide-spread occurrence in the Atlantic States of America[4], as well as in Nova Scotia and New Brunswick. In Maine five-sixths of the granitic rocks belong to this division. Several varieties are described by Kemp from Rhode Island and Connecticut, some containing allanite (Westerly), garnet (Stony Creek), and other special minerals. In some of these rocks microcline is a prominent constituent, as also in biotite-granites from Central Maryland[5] and Alabama[6]. The granite of Ilchester, Md., contains primary

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[1] Teall, pl. xxxv, fig. 1 [395]; Harker and Marr, *Q. J. G. S.* (1891) xlvii, 275–285, pl. xi, fig. 1.
[2] Sollas, *Trans. Roy. Ir. Acad.* (1894) xxx, 490.
[3] Craig, *Summary of Progress, Geol. Sur.* 1898, 28, and 1900, 22.
[4] Kemp, *Bull. Geol. Soc. Amer.* (1899) x, 377–382.
[5] Keyes, *15th Ann. Rep. U. S. Geol. Sur.* (1895) 696–730.
[6] Clements, *Bull. 5 Geol. Sur. Ala.* (1896) 139–142; Brooke, *ibid.* 185, 186.

epidote with allanite[1]. Coarse-grained porphyritic granites are extensively developed in Georgia[2], and similar rocks occur in North and South Carolina. They consist of quartz, orthoclase (with microperthite), microcline, oligoclase, and a variable amount of biotite.

Less abundant than the types characterized by micas, and usually of less acid composition, is *hornblende-granite* (Ger. Amphibolgranit), in which the distinctive mineral is a green hornblende, usually with biotite in addition. Some of the newer Palæozoic granites of Scotland are of this kind, such as that of Lairg[3] and Ord Hill[4] in Sutherland and the Criffel rock at Dalbeattie[5], in which, however, biotite often predominates. The Criffel granite, with others in Galloway, graduates into a quartz-diorite. The hornblende-granite of Loch Etive is coarse-grained, and has porphyritic crystals of orthoclase. The rock quarried at Mount Sorrel in Charnwood Forest, Leicestershire[6], is also in part a hornblende-granite, having that mineral associated with biotite. In Ireland a hornblende-granite has been described from Donegal[7], and another is associated with the Palæozoic biotite-granites of Newry (at Goragh Wood). Hornblende-granites of Tertiary age are found in Skye and Mull. In these the brownish green hornblende is associated with subordinate biotite. The rocks often shew a rude micrographic structure, and graduate into typical granophyres, in which the biotite, and to some extent the hornblende, give place to a greenish augite. A miarolitic structure is common, the cavities often obscured by calcite and other secondary products.

Hornblende-granites, often rich in sphene, are largely developed in Nevada and Utah[8]. In Massachussetts the

[1] Hobbs, *A. J. S.* (1889) xxxiii, 223–228.

[2] Watson, *Journ. of Geol.* (1901) ix, 97–122.

[3] Heddle, *M. M.* (1883) v, 178–184; Cole's *Stud. Micro. Sci.* No. 42 (plate); McMahon, *G. M.* 1899, 194–196.

[4] Cole's *Stud. Micro. Sci.* No. 38 (plate).

[5] Teall, *Mem. Geol. Sur. Scot., Expl. Sheet* 5 (1896) 41–43; *Ann. Rep. Geol. Sur.* for 1896, 41–44; and *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 507–525.

[6] Bonney, *Q. J. G. S.* (1878) xxxiv, 219.

[7] Hatch, *ibid.* (1888) xliv, 548–551.

[8] Zirkel, *Micro. Petrog. Fortieth Parallel* (1876) 40–52.

Rockport granite is a well-known example; that of Cape Ann has subordinate augite with the hornblende and biotite, and allanite as an accessory[1]; that of Quincy has instead of hornblende the deep blue amphibole-mineral riebeckite[2], which has also been described by Lacroix from St Peter's Dome, El Paso, Colorado. The Albany granite[3], in New Hampshire, carries porphyritic crystals of orthoclase with perthitic intergrowths of albite: biotite, hornblende, and sometimes pyroxene are present, and zircon is a conspicuous accessory.

If we exclude the granophyric varieties, *augite-granite* is by no means an abundant rock-type. An example, of Old Red Sandstone age, occurs in the Cheviots[4]. This consists of orthoclase, plagioclase, quartz, augite, exceptionally enstatite, biotite, iron-ores, and apatite, the quartz and orthoclase sometimes shewing a micrographic intergrowth. In some of the granites, graduating into granophyres, of Mull and the Red Hills of Skye augite is the dominant coloured mineral, but it tends to be converted to hornblende, and primary hornblende often accompanies it.

Augite-granites with anorthoclase as the dominant felspar ('soda-granites') are described from Minnesota[5], New Brunswick[6], and other parts of North America. These rocks also tend strongly to micrographic structures, and graduate into typical granophyres.

In Southern India a peculiar *hypersthene-granite* is of wide-spread occurrence, and has been described by Mr Holland[7] under the name charnockite. The typical rock consists of quartz and potash-felspar, with oligoclase, hypersthene, opaque iron-ore, and a little zircon. The dominant felspar seems to be microcline, often with parallel microperthitic intergrowths of plagioclase. The rock often shews some gneissic banding.

[1] Iddings, in Diller, 179, 180.
[2] Washington, *A. J. S.* (1898) vi, 180, 181.
[3] Hawes, *A. J. S.* (1881) xxi, 23.
[4] Teall, pl. xxxix, fig. 2, and *G. M.* 1885, 112–116; Kynaston, *Tr. Edin. G. S.* (1899) vii, 390–397.
[5] Grant, 21*st Ann. Rep. Geol. Sur. Minn.* (1894) and *Amer. Geol.* (1893) xi, 383–388.
[6] Mathew, *Tr. N. Y. Acad. Sci.* (1895) xiv, 204-208, pl. xvi, xvii.
[7] *Mem. Geol. Sur. Ind.* (1900) xxviii, 134–141.

Closely related to the granites is the rock known as *aplite* (granite-aplite). It occurs as veins in granite, but cutting the latter and traversing adjacent rocks, and by some petrologists it would be placed in the hypabyssal division. It is a fine-textured rock with 'panidiomorphic' to granulitic structure[1] and is somewhat more acid than the associated granite. A characteristic type occurs in connection with the muscovite-granites near Dublin (Dalkey and Killiney). It consists of microcline with some oligoclase, quartz, muscovite, and red garnet. An aplite at Meldon in Devonshire[2] is of similar character, but instead of garnet contains topaz and some colourless or pale tourmaline. The Crosby dyke[3] in the Isle of Man may be referred here. It consists essentially of a granular mosaic of clear felspars, quartz, and white mica, the dominant felspar being an albite. Besides the abundant small flakes of white mica, some larger hexagonal plates occur, and sometimes scattered quartz-grains or larger felspars. There are also a few garnets of very irregular shapes, giving a sponge-like appearance in section.

Washington[4] has described aplite dykes cutting the granite of Essex Co., Mass., and Pirsson notes aplites on Coanicut Island, R.I. In the Sierra Nevada region Turner[5] has remarked dykes of soda-aplite, consisting essentially of albite and quartz with sometimes muscovite, besides other aplites in which a potash-felspar is the dominant one.

Many of the rocks termed granulites by German writers doubtless belong here. They will be noticed in a later chapter (Chap. XXII.).

The *pegmatites* belonging to this family of rocks (granite-pegmatites) consist essentially of microcline or orthoclase and quartz, often with white mica and sometimes red garnet. The texture is often extremely coarse, and there is a frequent tendency to the graphic structure. Such rocks are extensively developed in connection with the Archæan gneiss of Sutherland.

[1] For plate of aplite from near Heidelberg see Berwerth, *Lief.* ii.
[2] Teall, p. 316 ; McMahon, *G. M.* 1901, 316–319.
[3] Hobson, *Q. J. G. S.* (1891) xlvii, 440.
[4] *Journ. Geol.* (1899) vii, 105, 106.
[5] *Ibid,* 156–158,

Others occur in Forfarshire[1]: these are rich in muscovite, and locally carry garnet or tourmaline. It may be observed that these British pegmatites are not rich in rare or special minerals. In the United States, on the other hand, many of the most noted mineral-localities are furnished by pegmatites of this kind; *e.g.* Stoneham and Hebron in Maine, Chesterfield in Massachussetts, Haddam in Connecticut, Pike's Peak in Colorado, and Harney's Peak in the Black Hills of Dakota. Central Maryland is another district[2]. Pegmatitic and aplitic dykes, both carrying red garnet, occur in the Montara granite of San Francisco[3], and such dykes, with only a small quantity of mica, are associated with the Santa Lucia granite near Monterey[4].

The *tourmaline-granites* appear as modifications of more normal granitic rocks. The tourmaline seems to take the place of the mica. As a further modification, the felspars may be replaced partly or wholly by tourmaline and quartz, the former sometimes occurring in little needles with radiate grouping imbedded in clear quartz. The extreme modification is a tourmaline-quartz-rock or *schorl-rock*, in which felspar is wholly wanting, while tourmaline may occur in two or more habits, as crystals or grains and as groups of needles. All these types are illustrated among the Cornish[5] and Dartmoor granites. A curious variety known as luxulyanite has been described by Prof. Bonney[6]. Here the conversion of felspars into clear quartz, crowded with radiate groups of tourmaline needles, can be traced in various stages, the little needles, about ·03 inch in length, giving pale brown and light indigo colours for longitudinal and transverse vibrations respectively, while a brown tourmaline in distinct grains has been supposed to represent the mica of the granite. A rock from Trowlesworthy Tor shews a similar replacement of felspar (fig. 8, *A*),

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[1] Barrow, *G. M.* 1892, 64; *Q. J. G. S.* (1893) xlix, 332–336.

[2] G. H. Williams, 15*th Ann. Rep. U. S. Geol. Sur.* (1895) 675–684.

[3] Lawson, *ibid.* 413.

[4] Lawson, *Bull. Dep. Geol. Univ. Cal.* (1893) i, 16, 17.

[5] For coloured figure of tourmaline-granite from Cornwall see Cohen (3), pl. xxii, fig. 2.

[6] *M. M.* (1877) i, 215–222; Semmons, *Pr. Liverp. G. S.* (1878) iii, 357, 358.

and has in addition irregular patches of isotropic fluor also enclosing needles of tourmaline[1].

The rock known as *greisen* (hyalomicte of French writers) consists essentially of quartz and white mica, which seems to be often a lithia-bearing variety. The Cornish greisens[2] are apparently a modification of the granite in the same sense as the tourmaline-rocks are, but with a different result. The place of the felspar is taken by mica and topaz, though tourmaline is also met with. It may be remarked that the topaz-rocks of Schneckenstein and Geyer in Saxony are closely allied to greisen. Greisen is also found in connection with the granite of the Scilly Isles. In Grainsgill, Cumberland[3], it has been formed at the expense of a pegmatitic modification of the Skiddaw granite, and the successive stages of the transformation can be studied. The white mica builds sometimes
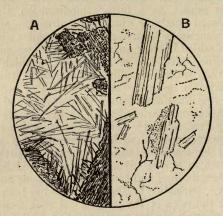
FIG. 8.   MODIFICATIONS OF GRANITE;   × 20.

A. Replacement of felspar by clear quartz full of tourmaline-needles, Trowlesworthy Tor, Cornwall : with remains of much-decomposed felspar [1361].   *B.*   Greisen, Grainsgill, Cumberland : consisting of quartz and muscovite with only occasional relics of turbid felspar [1547].

[1] Worth, *Trans. Roy. Geol. Soc. Cornw.* (1884) x, 177–188.
[2] Teall, 315.
[3] *Q. J. G. S.* (1895) li, 141.

rather large flakes (fig. 8, *B*), sometimes aggregates of small scales, and in both cases is embraced or enclosed by a moderately coarse mosaic of clear quartz. An American locality for typical greisen is Hill City in South Dakota.

In conclusion we will note some examples of the dark, fine-grained, ovoid patches frequently enclosed in granitic rocks, and regarded as *basic secretions* separated out from the granite-magma at an early stage, not necessarily *in situ*. Mr J. A. Phillips[1] described such patches from the muscovite-granites of Gready in Cornwall and Foggen Tor on Dartmoor and the biotite-granites of Shap and Peterhead, and he distinguished them from foreign fragments caught up and metamorphosed by the magma. The characteristic of the true secretions is that they consist of the same minerals as the enveloping rock, but contain the earliest products of crystallization—such as apatite, magnetite, and sphene—in larger proportions, and are also richer in the ferro-magnesian relatively to the felspathic elements of the rock. Sometimes, as in the Criffel granite[2], we may observe that hornblende is more plentiful as compared with biotite than in the normal rock, and similarly plagioclase felspar is more abundant relatively to orthoclase. The numerous dark patches in the Shap granite[3], rich in sphene and biotite (fig. 7, *B*), enclose, like the normal rock, large porphyritic crystals of orthoclase; but these are partially rounded and corroded, the margin of each crystal being replaced by plagioclase and quartz.

Among American rocks good illustrations are afforded by the hornblende-granite of the Wahsatch Range (Little Cottonwood Cañon, Utah), that of Essex County, Mass.[4], and the biotite-granite of Mount Ascutney, Vt[5].

[1] *Q. J. G. S.* (1880) xxxvi, 1–21; (1882) xxxviii, 216, 217.
[2] Teall, *Mem. Geol. Sur. Scot., Expl. of Sheet* 5 (1896) 42.
[3] *Q. J. G. S.* (1891) xlvii, 281, 282, pl. xi, fig. 2.
[4] Washington, *Journ. Geol.* (1898) vi, 795.
[5] Jaggar, *Bull.* 148 *U. S. G. S.* (1897) 68.

CHAPTER III.

SYENITES (*including* NEPHELINE-SYENITES).

THE syenites are even-grained, holocrystalline rocks consisting essentially of alkali-felspars, and in one group felspathoid minerals, with ferro-magnesian constituents, typically in smaller proportion, and various minor accessories. The texture is often rather coarse to medium-grained, and the structure is that characteristic of plutonic rocks, the several minerals following the normal order of crystallization, and most of them having only imperfect crystal outlines (hypidiomorphic structure of Rosenbusch). In many syenites, however, the order of crystallization is modified by simultaneous intergrowths of different minerals.

This family of rocks is less widely distributed and less abundant than the granites. Considered from a chemical point of view, it is characterized by an unusually high percentage of alkalies. In the syenites which depart farthest in this respect from the commoner types of igneous rocks, the character shews itself in the presence of felspathoid constituents and soda-bearing ferro-magnesian minerals.

The type characterized by hornblende and alkali-felspars is known as 'syenite proper'[1], or, for clearness, *hornblende-syenite*. When biotite more or less completely takes the place of hornblende, we have *mica-syenite ;* and when augite occurs prominently, often in company with one or both of the other

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[1] The original syenite of Werner was the hornblende-granite of Syene or Assouan on the Nile. The name, however, has come to be universally applied to the family under notice, rocks often hornblendic but typically free from quartz.

coloured minerals, *augite-syenite*. The group characterized by
the occurrence of nepheline or sodalite in addition to felspar is
named *nepheline-syenite*, or often elæolite-syenite, without dis-
tinction according to the dominant ferro-magnesian constituent,
though several types, mostly of restricted occurrence, have
received special names. A *leucite-syenite* is known only in
the form of rocks with pseudomorphs of orthoclase, elæolite,
muscovite, *etc.*, in the shape of leucite (fig. 11).

The occurrence of subordinate quartz in some syenites
gives rise to the varieties *quartz-syenite, quartz-mica-syenite,*
and *quartz-augite-syenite*, but free silica never occurs in the
nepheline-bearing group. On the other hand the coming in
of a lime-soda-felspar as a prominent constituent in addition
to the alkali-felspar gives rise to types intermediate between
true syenites and diorites, and to these the name *monzonite* is
sometimes given.

Constituent minerals. In mode of occurrence, in-
clusions, alteration-products, *etc.*, the felspars of syenites
resemble those of granites. Besides *orthoclase, microcline,*
and *albite* or *oligoclase*, there occur, especially in the augite-
and nepheline-syenites, felspars rich in both potash and soda,
known as soda-orthoclase, soda-microcline, anorthoclase, *etc.*
These are regarded by some mineralogists as intergrowths
on an ultra-microscopic scale of a potash- and a soda-felspar
(*cryptoperthite*). An evident parallel intergrowth of albite
and microcline or albite and orthoclase (*microperthite*) is also
frequent in the same rocks.

When nepheline occurs, it is of the variety known as
elæolite, in larger and less perfect crystals than the nepheline
of volcanic rocks. If idiomorphic, it forms hexagonal prisms
with the basal plane bevelled by narrow pyramid-faces. In
more shapeless crystals the straight extinction can be verified
by reference to rows of inclusions which follow the direction
of the vertical axis, and seem to determine the alteration of
the mineral. The elæolite is colourless or often rather turbid.
It gives rise by decomposition to various soda-zeolites or to
moderately brightly polarizing prisms, fibres, and aggregates of
cancrinite. A frequent associate of elæolite is *sodalite*, in
dodecahedra or in allotriomorphic crystal-plates and wedges.

It is colourless or faint blue in slices, and is easily recognized by its isotropic behaviour. It encloses fluid-pores, microlites of ægirine, *etc.*, and secondary products similar to those of elæolite.

The common *hornblende* of syenites is partly idiomorphic but without terminal planes. It is of the green pleochroic variety, giving in vertical sections a maximum extinction-angle of 12° to 16°. Its inclusions and alteration-products are the same as in granite. Some augite-syenites contain the soda-amphibole *barkevicite* with intense brown absorption and pleochroism and an extinction-angle of about 12°.

The *augite*, when it occurs as an accessory, is colourless or very pale green, with the same properties as in granite. In the augite-syenites it is sometimes pale green with faint pleochroism, sometimes pale brown to violet-brown with very distinct pleochroism. Various types of schiller- and diallage-structures are sometimes seen, and may affect only a portion— usually the interior—of a crystal (fig. 10). A green pleochroic *ægirine* occurs in some augite-syenites and many nepheline-syenites, and intergrowths of this with augite are not uncommon.

The *biotite* of the syenites is deep brown, becoming green only by secondary changes. In some augite- and nepheline-syenites vibrations parallel to the cleavage-traces are almost completely absorbed. The mineral is roughly idiomorphic, except when intergrown with hornblende or augite.

When *quartz* occurs, it has the same characters as in granite, but is never very abundant. It does not occur in the nepheline-syenites and their allies. Most syenites contain plenty of *sphene* in good crystals shewing the cleavages and often the characteristic twinning[1]. *Zircon* is common in small prisms with pyramidal terminations, as in the granites. In some of the augite-syenites, however, it builds large crystals of simple pyramidal form. It is easily identified by its limpid appearance and extremely high refringence and bire-fringence. *Apatite* in colourless needles is widely distributed in syenites. The iron-ores are variable in quantity: they

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[1] See Rosenbusch-Iddings, pl. xi, fig. 3; xxiii, fig. 1: Cohen (3), pl. xxx, fig. 1.

include *magnetite, ilmenite,* and *hœmatite,* the last two often in thin flakes enclosed in the felspars. An occasional accessory is *perofskite* in small octahedra, distinguished by their very high refractive index and feeble double refraction. Special types contain *melanite* garnet, brown in slices and always isotropic.

Structure. The texture of the syenites and the mutual relations of their constituent minerals are normally similar to those observed in the granites, Rosenbusch's 'order of consolidation', being, as a rule, followed. In the typical hornblende-syenites there are few peculiarities. When quartz enters, it may be intergrown in micrographic fashion with part of the orthoclase, and this is specially the case in some augite-syenites. When plagioclase felspar is abundant, it is sometimes moulded by shapeless plates of orthoclase, and in the same rocks reversals of order between the bisilicates and the felspars may often be noticed.

Where the felspathoids occur, their place in the order of crystallization is a variable one. These minerals usually precede the felspars, but may continue to crystallize to a later stage. The nepheline-syenites not infrequently take on a porphyritic character: often too a 'trachytic' structure, marked by a partial parallelism of felspars with tabular habit.

Some syenites contain basic secretions, acid veins, pegmatite fringes and other peculiarities noticed under the granites. Parallel and gneissic structures sometimes come in locally (*e.g.* Plauen'scher Grund).

Leading types. Although typical hornblende-syenites occur in this country (*e.g.* Malvern), very little has been written about them, and for the type-rocks we must go to foreign occurrences. The name 'syenite' as found in many of the earlier writings and maps in this country is to be understood in the old sense of hornblende-granite (including also granophyre, *etc.*) and the identification of hornblende is in very many cases erroneous. For example, the so-called 'syenites' of St David's, of Ennerdale, of Carrock Fell, *etc.,* have no claim to the title, whether the word be used in its original or its modern sense.

The rock taken as the type of *hornblende-syenite* is that of Plauen'scher Grund near Dresden (fig. 9). It is composed

essentially of orthoclase, with only subordinate oligoclase, and
green hornblende. Apatite, magnetite, and sphene occur as
accessories, and in places a little quartz. There is a variety
in which biotite occurs in addition to the hornblende. The
rock encloses dark basic secretions richer in plagioclase, horn-
blende, apatite, magnetite, and sphene. Further there are
pegmatoid acid veins of coarse texture, in which the more
basic minerals occur only sparingly, while quartz is plentiful.
Almost the same description applies to other Saxon syenites,
such as that of Meissen, which, however, has rather more
oligoclase and brown mica, and further contains a little more
quartz, either in grains or in micrographic intergrowth.
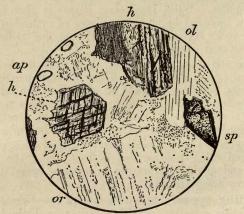
FIG. 9. HORNBLENDE-SYENITE, PLAUEN'SCHER GRUND, DRESDEN; × 20.

Shewing hornblende (*h*), orthoclase (*or*), subordinate oligoclase (*ol*),
sphene (*sp*), and apatite (*ap*) [47].

A syenite like that of Dresden, but sometimes rich in
biotite, occurs near Salem, Mass.[1] More felspathic varieties
have been noted from Curtis Point, Beverley, Mass.[2] (with
arfvedsonite-like hornblende) and Albany, N.H. (with blue
riebeckite).

[1] Wadsworth, *G. M.* 1885, 207.
[2] Sears, *Bull. Essex Inst.* (1891) xxiii.

Such rocks as that of Meissen may with propriety be termed *quartz-syenite* (quartz-hornblende-syenite), and form a connecting link with the hornblende-granites. Again, when a triclinic felspar becomes predominant we have transitions to quartz-diorite (*e.g.* Weinheim, in the Odenwald, near Heidelberg). Brögger's red quartz-syenite (Nordmark type) from the Christiania district also has oligoclase in addition to the dominant orthoclase, and sometimes a microperthitic intergrowth of albite and orthoclase. Biotite and hornblende are the chief ferro-magnesian constituents, but green augite and ægirine also occur. This type is known in America, *e.g.* in the Montreal district[1]. In Sutherland the large intrusive mass of Cnoc na Sròine[2], near Loch Borolan consists mainly of a quartz-syenite approximating to the Nordmark type, but it graduates on the one hand into granite and on the other into quartzless syenite and other more remarkable types.

The *mica-syenite* type, in which biotite predominates over hornblende, is of uncommon occurrence, except as a local variety of hornblende-syenite. More often there is some quartz present, and such rocks are found graduating into biotite-granite. Rosenbusch mentions mica-syenites from Canada; one from Star Hill Mine, Portland West, P. Q., rich in apatite ; another from Blessington Mine, Inchinbrooke, P. O., with some augite as well as mica. These rocks are free from quartz or plagioclase.

Among *quartz-augite-syenites* may be mentioned Brögger's Aker type from the Christiania district, which contains plenty of plagioclase as well as orthoclase, and has resemblances to the Monzoni rocks. Biotite occurs in addition to the pale green augite. A similar, but rather more acid, rock from Essex County, Mass., has primary hornblende in addition to augite[3].

Other quartz-syenites characterized by augite shew a strong tendency to micrographic intergrowth of quartz and felspar. This is seen in the larger pre-Carboniferous intrusions of

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[1] Dresser, *Amer. Geol.* (1901) xxviii, 207, 208 (Shefford Mt.).
[2] Teall, *G. M.* 1900, 385–392.
[3] Washington, *Journ. Geol.* (1898) vi, 797.

Leicestershire (excepting the Mount Sorrel granite), which indeed may be classed as a less acid type of granophyre. The augite tends to pass into uralitic hornblende, and epidote is a characteristic secondary product in the rocks. Examples are seen at Groby, Bradgate Park, Markfield, and Garendon, all in the Charnwood Forest district[1].

A special type of *augite-syenite* is presented by the Triassic intrusions of Monzoni in the southern Tirol (monzonite[2] of De Lapparent), which are associated with diabases and other basic rocks. Orthoclase is sometimes the only felspar, but usually there is a plagioclase in addition, forming idiomorphic crystals enclosed with the other minerals by plates of orthoclase. The augite often passes over into green hornblende, but the latter mineral also occurs as an original constituent. Biotite is usually present, in flakes sometimes earlier, sometimes later, than the plagioclase. Sphene is frequent, and zircon is often enclosed by the mica. Other constituents are apatite, magnetite, and pyrites, and in some varieties a little interstitial quartz.

In America Weed and Pirsson have described a rock closely resembling the typical monzonites from Yogo Peak, Montana[3]. This rock, with about equal amounts of felspar and augite, graduates on the one hand into a more felspathic augite-syenite and on the other into a thoroughly basic type very rich in augite. This last (Shonkin type) was first distinguished by the same writers at Square Butte in the Highwood Mts, Mont.[4] It consists of predominant augite with orthoclase, albite, and anorthoclase, apatite, biotite, olivine, *etc.*, and may be compared with the basic modifications of the rocks of Monzoni ('pyroxenites' of Brögger).

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[1] Bonney, *Q. J. G. S.* (1878) xxxiv, 214–218.

[2] Brögger makes a distinct family of monzonites, characterized by the occurrence of orthoclase and plagioclase felspars in about equal amounts, and including more and less acid members.

[3] *A. J. S.* (1895) l, 467–479; *20th Ann. Rep. U. S. Geol. Sur.* (1900) part III, 475–479. For another American occurrence see Tower and Smith, *19th Ann. Rep. U. S. Geol. Sur.* (1899) part III, 645, 646 (Tintic Mts, Utah).

[4] *Bull. Geol. Soc. Amer.* (1895) vi, 408–415; *cf. 20th Ann. Rep. U. S. Geol. Sur.* (1900) part III, 479–484, pl. LXXII.

From Magnet Cove, Arkansas, Washington[1] describes a similar but nepheline-bearing rock under the name 'covite.'

A remarkable basic rock, comparable with Brögger's olivine-monzonite, occurs at Kentallen and other places in Argyllshire (Kentallen type)[2]. It consists of olivine, pale green augite, plagioclase, and interstitial biotite and orthoclase. It shews considerable variation, sometimes approximating to the Shonkin type.

A peculiar augite-syenite (Laurvig type), allied in some respects to the nepheline-syenites, occurs among the Devonian intrusions of the Christiania district. While augite is usually the dominant ferro-magnesian element, it is often accompanied by biotite, ægirine, hornblende, or arfvedsonite, and the rock thus passes into mica-syenite, *etc.* Alkali-felspars (orthoclase, microcline, albite, cryptoperthite, *etc.*) make up the bulk of the rock, and are often intergrown with one another. Not infrequently they have a schiller-structure. A little quartz is rarely present; on the other hand elæolite and sometimes olivine may occur as minor accessories. The augite is occasionally green, but commonly light brown with a violet tone and slight pleochroism: schiller-structure is common. The hornblende is green or occasionally brown, the biotite a very deep brown. The latter mineral is roughly idiomorphic, except when it is massed round magnetite or forms a marginal intergrowth with augite. The iron-ores are magnetite and sometimes hæmatite: apatite is universal, but sphene is typically absent. Zircon is a constant accessory, and sometimes builds large crystals, giving the variety 'zircon-syenite' of von Buch and other early writers. These augite-syenites are common as boulders[3] on our East coast (fig. 10).

Other augite-syenites rich in microperthitic intergrowths occur in New Hampshire (Jackson, Stark, and Columbia) and in the Sawtooth Mts of Texas. Examples having ægirine-augite as the dominant coloured silicate come from the

[1] *Journ. Geol.* (1901) ix, 612–615.

[2] Teall, pl. xvi, fig. 1, and *Ann. Rep. Geol. Sur.* for 1896, 22, 23; Hill and Kynaston, *Q. J. G. S.* (1900) lvi, 531–540, pl. xxix, xxx; Hill, *Summary of Progress, Geol. Sur.* for 1899, 48–53.

[3] *Proc. Yorks. Geol. Pol. Soc.* (1889–90) xi, 303, 304, 410.

Bearpaw Mts in Montana[1] and Mosquez Cañon, Texas, while a more typical *ægirine-syenite* is recorded from Fourche Mt., Ark.
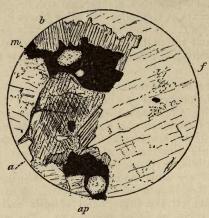
The minerals seen are cryptoperthite felspar (*f*) in large plates, augite (*a*) with schiller-structure in the interior of the crystal, deep brown biotite (*b*), magnetite (*m*), and apatite (*ap*) [1841].

As a connecting link between syenites proper and nepheline-syenite we have the Pulaski type of J. F. Williams[2] from Fourche Mt., near Little Rock, Arkansas, in which nepheline is only an accessory constituent. Various alkali-felspars occur, soda-felspar predominating, and various ferro-magnesian minerals, of which hornblende is the chief. A neighbouring rock, described under the name elæolite-syenite, seems to be not essentially different[3]. The same type occurs associated with nepheline-syenites in other localities, *e.g.* near Montreal[4]

[1] Weed and Pirsson, *A. J. S.* (1896) ii, 136, 137.

[2] *Ign. Rocks of Arkansas*, vol. ii of *Ann. Rep. Geol. Sur. Ark.* for 1890, 55–69; Diller, pp. 194–197.

[3] *Ign. Rocks Ark.* 74–81; Washington, *Journ. Geol.* (1901) ix, 610.

[4] Dresser, *Amer. Geol.* (1901) xxviii, 209, 210 (Shefford Mt.).

and in Essex County, Mass.[1] Another American rock, from Red Hill in New Hampshire[2], is referred by Rosenbusch to the Umptek type of Ramsay (from the Kola peninsula in Finland).

Of true nepheline-syenites a good example is the coarse-grained Laurdal type of the Christiania district. It differs from the neighbouring Laurvig rock chiefly in the presence of abundant nepheline in large partly idiomorphic crystals and often sodalite. There is, as before, considerable variety of alkali-felspars, cryptoperthite predominating. The ferro-magnesian minerals include deep-brown mica and either a greenish ægirine-augite or the violet-brown augite noted in the other rock. Apatite is abundant.

A well-known nepheline-syenite is that of Sierra de Monchique in Portugal[3] (Foya type). Here the felspar is orthoclase and is in excess of the nepheline (elæolite); sodalite is often present; the coloured minerals are subordinate hornblende, augite edged with ægirine-augite, and biotite; while apatite, magnetite, and abundant sphene are also present. Rocks generally comparable with this occur in Brazil, near Montreal (with melanite), at Salem and Marblehead[4] (Mass.), in the Crazy Mts (Mont.)[5], in the Cripple Creek district (Colo.)[6], at Mt. Ord and Paisano Pass (Tex.)[7], and at several localities in Arkansas[8]. Some of the Arkansas rocks have porphyritic modifications. At Beemerville (N.J.)[9], again, occurs a variety with very large crystals of orthoclase,

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[1] Washington, *Journ. Geol.* (1898) vi, 804–807.

[2] Bayley, *Bull. Geol. Soc. Amer.* (1892) iii, 245–253.

[3] Sheibner, *Q. J. G. S.* (1879) xxxv, 42–47, pl. ii.

[4] Wadsworth, *Proc. Bost. Soc. Nat. Hist.* (1882) xxi, 406 ; *G. M.* 1885, 208, 209 ; Sears, *Bull. Essex Inst.* (1893) xxv ; Washington, *Journ. Geol.* (1898) vi, 801–804.

[5] Wolff and Tarr, *Bull. Mus. Comp. Zool. Harv.* (1893) xvi, 230, 231.

[6] Cross, 16th *Ann. Rep. U. S. Geol. Sur.* (1895) part ii, 43, 44.

[7] Osann, 4th *Ann. Rep. Geol. Sur. Tex.* (1893) 126–129.

[8] J. F. Williams, *Ign. Rocks Ark.* (1890) 85–87 (Fourche Mt.); 132–139 (Saline Co.) ; 233–238 (Magnet Cove) ; 349, 350 (Potash Sulphur Springs). On the Magnet Cove (Diamond Jo) rock see also Washington, *Journ. Geol.* (1891) ix, 610, 611.

[9] Emerson, *A. J. S.* (1882) xxiii, 302–308; Kemp, *Trans. N. Y. Acad. Sci.* (1892) xi, 63 ; Iddings in Diller, 209, 210.

the interspaces filled by little prisms of ægirine and abundant elæolite, partly changed to cancrinite.

Among other nepheline-syenites may be mentioned the Miask type from the Urals, in which a deep brown mica is the most prominent constituent, plagioclase is abundant, frequently intergrown with the orthoclase, and zircon is a characteristic accessory. The Ditro type, from Transylvania, also carries mica, but much less plentifully: it is distinguished by its abundance of allotriomorphic sodalite and by the variety and intimate intergrowths of its felspars, which include microcline as well as orthoclase and oligoclase. Cancrinite, sphene, zircon, and perofskite also occur[1]. In the Litchfield type[2], from Maine, albite constitutes about half of the rock, the other minerals being orthoclase, microcline, elæolite, sodalite, cancrinite, a deep green biotite (lepidomelane), and a little zircon. A variety from Dungannon[3] in Ontario resembles the Litchfield rock in the predominance of a soda-felspar, but is richer in nepheline. In one modification the felspar disappears, and the rock consists merely of nepheline with a little hornblende or mica (hornblende-ijolite): an interesting feature is the occurrence of corundum[4]. The ijolite of Ramsay and Berghell, from Finland, consists essentially of nepheline and augite, usually with melanite (a titaniferous variety), felspar being wholly absent. A rock of this type forms part of the curious igneous complex of Magnet Cove in Arkansas[5].

The only nepheline-syenite known in Britain occurs in association with other syenitic rocks on Cnoc na Sròine in Sutherland. As described by Mr Teall[6], it consists of nepheline and alkali-felspar in about equal amounts, with some greenish biotite and melanite garnet.

[1] For coloured figures of these rocks see Fouqué and Lévy, pl. XLV, fig. 1.

[2] Bayley, *Bull. Geol. Soc. Amer.* (1892) iii, 235–241, and in Diller, 201–209, pl. XXIX.

[3] Adams, *A. J. S.* (1894) xlviii, 10–16.

[4] Coleman, *Rep. Bur. Mines, Toronto* (1899) viii, part II, 250–253.

[5] Washington, *Bull. Geol. Soc. Amer.* (1900) xi, 400 ; *Journ. Geol.* (1901) ix, 618. This is the 'Ridge type' of Williams, *Ign. Rocks Ark.* (1890) 229–231.

[6] *G. M.* 1900, 387, 388.

Associated with the rock just mentioned is a very interesting one which may be styled a *leucite-syenite* (Borolan type)[1]. It is exposed at Loch Borolan, and occurs also in the adjacent part of Ross. The rock consists essentially of orthoclase, a brown melanite garnet, and a green or green-brown biotite. A green monoclinic pyroxene is present in many examples:
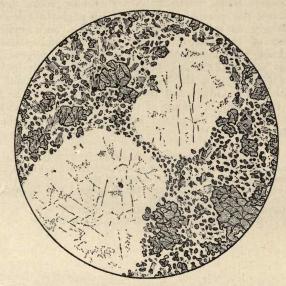

Fig. 11. MELANITE-LEUCITE-SYENITE (BOROLANITE), LOCH BOROLAN, SUTHERLAND; × 5.

Composed essentially of orthoclase and the iron-garnet (melanite) with some pale green biotite. The clear spaces represent pseudomorphs of orthoclase after leucite [2956].

a brown pleochroic sphene, apatite, and magnetite occur as accessories. Much of the orthoclase occurs in the form of rounded patches, $\frac{1}{4}$ to $\frac{3}{4}$ inch in diameter, which replace leucite crystals (fig. 11). A similar rock, differing by the

[1] Dakyns and Teall, *Tr. Roy. Soc. Edin.* (1892) xxxvii, 163–172, with plate; Teall, *G. M.* 1900, 389.

presence of abundant nepheline, is found in the igneous complex of Magnet Cove, Ark.[1]

A *sodalite-syenite*, with little or no elæolite, seems to be an uncommon type. It has been found in the Highwood Mts of Montana[2] and at Cottonwood Creek[3] in the same state.

Among special modifications of syenitic rocks may be mentioned the *syenite-aplites* and *syenite-pegmatites* described by Brögger as associated with the augite- and nepheline-syenites of the Christiania district. The pegmatites are remarkable not only for the frequent perthitic intergrowths of potash- and soda-felspars, but also for graphic intergrowths of the felspars with the ferro-magnesian minerals and with elæolite and sodalite; and they are famous as the home of many rare minerals. Some of these features are reproduced in the pegmatites associated with the Arkansas nepheline-syenites[4].

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[1] J. F. Williams, *Ign. Rocks Ark.* (1890) 267–276; Washington, *Bull. Geol. Soc. Amer.* (1900) xi, 399, and *Journ. Geol.* (1901) ix, 615–617. The latter author gives to this type the name 'arkite.'

[2] Lindgren, *A. J. S.* (1893) xlv, 290–297; Weed and Pirsson, *Bull. Geol. Soc. Amer.* (1895) vi, 416, 417.

[3] Merrill, *Pr. U. S. Nat. Mus.* (1894) xvii, 671–673.

[4] J. F. Williams, *Ign. Rocks Ark.* (1890) 143–146, 238–258.

CHAPTER IV.

DIORITES.

THE diorites are plutonic rocks of medium to coarse texture, consisting essentially of a soda-lime felspar and hornblende, with less important constituents. The family so defined cannot be regarded as a natural one, its members ranging in chemical composition from sub-acid to thoroughly basic. The gabbros (characterized by pyroxenes in place of hornblende) also include intermediate as well as basic rocks, and the distinction between the hornblende- and augite-bearing types is rather an artificial one. It was established before the strong tendency of augite to pass over into hornblende was thoroughly appreciated : later research has shewn the certainty of some, and the possibility of many, of the rocks that have been termed diorites being really amphibolized pyroxenic rocks.

The more acid diorites contain free silica (*quartz-diorites*), and, except for the smaller proportion of quartz and the nature of the felspars, do not differ much from the hornblende-granites[1]. They may have biotite in addition to hornblende (*quartz-mica-diorites*), or in some cases augite. In the *diorites* proper, without quartz, mica is not common, but the hornblende may be accompanied by augite or sometimes enstatite. The hornblende is more abundant relatively to the felspar than in the preceding types, and some of the more basic diorites consist chiefly of hornblende. These are the 'amphibolites' of some authors[2]. In some types olivine enters as a constituent (*olivine-diorites*).

[1] See Berwerth, *Lief.* 1, quartz-diorite from the Vosges.
[2] For a hornblende-rock (local modification of a diorite) see Fouqué and Michel Lévy, pl. xxiii.

The occurrence of felspathoid minerals in dioritic rocks seems to be very exceptional. The *theralites* of Rosenbusch may be regarded as nepheline-diorites and nepheline-gabbros, but comparatively little is yet known of such rocks.
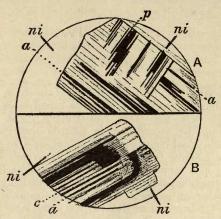

Fig. 12.   Crystals of plagioclase felspar in quartz-mica-diorite, Beinn Nevis; × 20, crossed nicols.

The vibration-planes of the nicols are indicated by the lines (*ni*). *A* shews the association of twin-lamellation on the albite (*a*) and pericline (*p*) laws. *B* shews carlsbad twinning (*c*) combined with albite-twin-lamellation (*a*) and with zonary banding [397].

Constituent minerals. The felspar of the diorites is *oligoclase, andesine*, or *labradorite*, or exceptionally a more basic variety. The twin-lamellation on the albite type is often accompanied by pericline or carlsbad twinning (fig. 12, *A*). In the quartz-diorites especially, the crystals frequently shew between crossed nicols a marked zonary banding, the central and marginal portions of a crystal often giving widely different extinction-angles, and the successive layers growing more acid from within outwards (fig. 12, *B*). In natural light the zones of growth may be indicated by the disposition of fluid-pores, minute scales of hæmatite, or other inclusions. The crystals are often clouded by a fine dust (probably kaolin), and may also furnish by their alteration scales of colourless mica

(paragonite ?), grains of epidote, calcite, *etc.* A little *ortho-clase* may be present as an accessory, behaving in the quartz-diorites as in granites, while in typical diorites it occurs interstitially.

The *hornblende*, when idiomorphic, shews the prism-faces and usually the clinopinacoid, and terminal planes are often present. Twinning is common, and the prismatic cleavage is always well pronounced. In the quartz-diorites the mineral, usually in imperfect crystals, is green, as in granites; in more normal diorites it has brownish-green or greenish-brown colours; and in the most basic types the original hornblende is usually of some greenish shade of brown, or even approaches the deep brown of 'basaltic hornblende.' Pale colours result from bleaching, or are found in secondary outgrowths[1] of the brown crystals, and these are green rather than brown. Two kinds of outgrowth or enlargement of hornblende crystals are to be observed in some basic diorites, the new growth being in
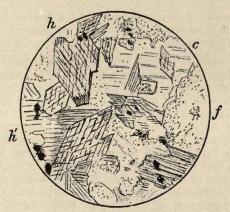
FIG. 13.   BASIC DIORITE, LLYS EINION, NEAR LLANERCHYMEDD,
ANGLESEY; × 20.

The original idiomorphic brown hornblende has an extension of green hornblende on the clinopinacoid faces (*h*) and also a secondary fibrous outgrowth on the terminal planes (*h'*). The felspar (*f*) is much decomposed, and crystalline calcite (*c*) has been produced [539].

[1] Van Hise, *A. J. S.* (1887) xxxiii, 385–388, with figures.

both cases in crystalline continuity with the old. In one case a growth of green hornblende takes place on the clinopinacoid faces so as to extend the crystal, with idiomorphic contour, in the direction of the orthodiagonal: in the other case pale green or colourless hornblende grows so as to extend a crystal in the direction of its length, and may present new crystal-faces, or abut on another crystal, or frequently terminate in a ragged fibrous fringe. The second type of outgrowth at least is of secondary origin, and is formed at the expense of other minerals (fig. 13). Besides more usual types of alteration[1], the brown hornblende of diorites may shew bleaching, with separation of magnetite, or it may be converted into a brown mica or into green blades of actinolite.

The deep brown *biotite* of the diorites occurs in idiomorphic flakes, or sometimes intergrown with hornblende. It is usually not rich in inclusions. It becomes green only by partial decomposition.

The rhombic pyroxene found in a few diorites is a variety poor in iron (*enstatite*) and is usually converted into pseudomorphous pale bastite.

When *augite* is present, it is of a variety sensibly colourless in slices. If idiomorphic, it shews the octagonal cross-section due to equal development of the pinacoids and prism-faces, with good prismatic cleavage and not infrequently lamellar twinning parallel to the orthopinacoid. A not uncommon feature in diorites is a parallel growth of augite and hornblende, a crystal-grain of the former mineral constituting a kernel, round which a shell of brown hornblende has grown, and this seems to occur specially in the neighbourhood of grains of iron-ore. This must be distinguished from another phenomenon frequent in the augite-bearing diorites, *viz.* the conversion of augite into brown hornblende as a secondary change[2]. This process usually begins at the margin of a crystal or grain, but proceeds irregularly, shewing a very intricate boundary between the two minerals and often ragged scraps of one enclosed by the other. When the conversion is

[1] Zirkel, *Micro. Petr. Fortieth Parallel*, pl. III, figs. 2, 3, 4.
[2] *Q. J. G. S.* (1888) xliv, 452, 453 ; *M. M.* (1888) viii, 31–34.

complete, the secondary hornblende can be distinguished from original only by inference, as, *e.g.* when it shews the external form of augite. In both phenomena the augite and hornblende have their plane of symmetry and longitudinal axis in common, and in longitudinal sections both extinguish on the same side of the axis.

The *quartz* of quartz-diorites has the same general characters as that of granites.

The *olivine* which occurs in some basic diorites is often in rather rounded crystals enclosed by the hornblende. It is easily recognised by its high refractive index and very strong double refraction. The mineral is readily altered into serpentine, carbonates, and especially pale fibrous amphibole, the last often grown in crystalline continuity with adjacent original hornblende.

Among the iron-ores, *magnetite* is the most usual, but *ilmenite* is also found. Common accessories in some varieties are *zircon* and *sphene* in characteristic crystals. *Apatite* is general, and in some basic diorites abundant: in the coarse-grained rocks it sometimes builds rather large prisms.

Structure. The structure of the dioritic rocks is variable. In the quartz-diorites[1] the mutual relations of the minerals are those noticed in granites, though sometimes a part of the felspar has crystallized before the ferro-magnesian minerals. A micrographic intergrowth of quartz and felspar is not infrequent. Many of the quartzless diorites also follow what may be called the normal order of crystallization. Rosenbusch points out that the most marked pauses in the process of consolidation have occurred before the separation of the ferro-magnesian minerals and after that of the plagioclase; so that while the apatite, sphene, *etc.*, and the plagioclase may be markedly idiomorphic, the hornblende, biotite, and augite tend to occur in much more irregularly shaped crystals. When a miarolitic structure results from the tendency to idiomorphism in the latest crystallized elements, it is commonly obscured by the cavities becoming filled by calcite and other secondary products.

[1] Berwerth, *Lief.* 1 (Schwarzenberg, Vosges).

A different type of structure, though connected by transitions with the preceding, is found in many dioritic rocks. Here the plagioclase has crystallized earlier, or at least ceased to crystallize earlier, than the bisilicates; so that the dominant felspar presents idiomorphic outlines to the hornblende and (if present) augite. These latter may wrap round, or even enclose, the felspar crystals, giving an 'ophitic' structure identical with that described below as characteristic of the diabases, and the hornblendic rocks exhibiting this character have sometimes been termed hornblende-diabases. Such a structure is found more or less markedly in many of the more basic diorites, and is especially common in rocks in which the hornblende is in great part derivative after augite, but original hornblende moulded on felspar is also found.

Pegmatoid and aplitic structures are less common in this family than in the granites and syenites.

A porphyritic structure is not common in true diorites, but may come in as a marginal modification of a boss or stock, the porphyritic elements being crystals of hornblende or felspar.

As a more special type of structure may be mentioned the orbicular (in the so-called corsite or napoleonite), where the bulk of the rock consists of spheroidal growths. These have a radial structure and consist of concentric shells composed essentially of hornblende and felspar alternately. A well-known rock of this character comes from San Lucia di Tallano in Corsica[1].

Leading types. The *quartz-diorite* of the Adamello Alps, on the border of Italy and the Tirol (Tonale type) comes very near in characters to some granites[2], and has also

[1] Cohen (3), pl. LXXI, fig. 3; Robertson, *Tr. G. S. Glasgow* (1883) vii, 210.

[2] This is the '*tonalite*' of vom Rath. Since it is an extreme type, and is classed by some petrologists with the granites, it is confusing to extend this name, as some writers have done, to all the quartz-diorites. Brögger restricts the term to the type free from any alkali-felspar; that with both an alkali- and a lime-soda-felspar he styles *adamellite*, and regards as the most acid member of his monzonite family.

points in common with the Monzoni syenites. The dominant felspar is a striated plagioclase, often shewing zonary banding and with a strong tendency to idiomorphic outlines; but there is frequently clear orthoclase in addition, in irregular crystal plates moulded on or enclosing the triclinic felspar. Biotite is the most constant coloured element, but hornblende is also abundant. The mutual relations of the two are variable, and both may enclose the plagioclase. Interstitial quartz is abundant; patches of magnetite are often prominent; and zircon in little well-built prisms is of general occurrence.

Many of the Scottish 'granites' of Upper Palæozoic age are better classed as quartz-diorites, and shew well the interstitial quartz, the zoned plagioclase crystals, and other characteristic features. A good quartz-mica-diorite comes from the lower part of Beinn Nevis. Other quartz-diorites occur about Garabal Hill, near the head of Loch Lomond[1], and shew gradations on the one hand into granites, on the other into quartzless diorites (including mica-diorite and augite-diorite). Similar gradations are exhibited by the Beinn Cruachan rock, which is in the main of the Tonale type[2]. Of the three main masses of the 'Galloway granites' one, that of Criffel, has as its prevalent variety a quartz-diorite of the same type.

In Wicklow, to the east of Rathdrum, occur quartz-diorites and quartz-mica-diorites which in some particulars approximate to the granites, subordinate orthoclase accompanying the dominant triclinic felspar. The other minerals are pale green hornblende, ragged flakes of biotite, abundant quartz, apatite, and sometimes a little colourless augite[3]. The augite-diorites, a common type in Wicklow, sometimes contain interstitial quartz.

In the United States, as in Britain, numerous rocks belonging here have been designated granite, or sometimes granite-diorite. A type with subordinate potash-felspar, largely developed in the Sierra Nevada of California, has

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[1] Dakyns and Teall, *Q. J. G. S.* (1892) xlviii, 104–120.

[2] Kynaston, *Ann. Rep. Geol. Sur.* for 1896, 24.

[3] Hatch, *G. M.* 1889, 262, 263; see also Watts, *Guide*, 34.

been styled 'granodiorite,' and is regarded by Lindgren[1] as intermediate between true quartz-diorite and quartz-monzonite. Of similar nature is the rock of Butte City, Mont., the chief constituents of which are acid labradorite, orthoclase, quartz, and green hornblende, with subordinate biotite[2].

As a typical quartz-diorite may be cited that described by Iddings[3] from Electric Peak in the Yellowstone Park. Here the dominant felspar ranges from oligoclase to labradorite, and there is sometimes orthoclase in addition ; the quartz is in allotriomorphic grains ; and the other constituents are biotite, hornblende, augite, hypersthene, and magnetite. Parallel intergrowths are frequent among the ferro-magnesian minerals, hypersthene being bordered by augite and the pyroxenes by biotite and hornblende[4]. A porphyritic quartz-mica-diorite was described by G. H. Williams[5] among the varied dioritic rocks of the Cortlandt district. The large felspar crystals are strongly zoned, but only occasionally lamellated.

A *mica-diorite*, without quartz, is not a common type. It is found as a local modification of biotite-granite between Carrick Mt. and Arklow, in Wicklow. Mr Teall[6] describes a good example from Pen Voose in the Lizard district, Cornwall. This consists essentially of felspar and a reddish brown mica with only quite subordinate green hornblende and accessory sphene. From Allt-a-Mhullin, south of Lochinver, Sutherland, the same author notes a mica-diorite with interstitial felspar. Among the Cortlandt rocks, on the Hudson River, a pure mica-diorite occurs, beside various mica-hornblende-diorites. It is a rather coarse-grained aggregate of plagioclase (oligoclase-andesine) and very deeply coloured biotite, with accessory epidote, magnetite, abundant apatite, and sometimes a little

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[1] *A. J. S.* (1897) iii, 308–312; see also Turner, *17th Ann. Rep. U. S. Geol. Sur.* (1896) 636, 637, pl. XLII, A.

[2] Weed, *Journ. Geol.* (1899) vii, 740–744.

[3] See *12th Ann. Rep. U. S. Geol. Sur.* (1892) 595–609; also in Diller, 243, 244.

[4] *Ibid.* pl. L.

[5] *A. J. S.* (1888) xxxv, 446.

[6] Pl. XXXII, fig. 1 ; XLVII, fig. 3.

quartz[1]. Mica-diorite has been noted near the Comstock Lode, Nevada.

Of simple *hornblende-diorite*, without quartz, good examples, of Palæozoic age, are found in Warwickshire and other parts of the Midlands. In the rock of Atherstone, Hartshill, the brown hornblende is in part idiomorphic towards the turbid felspar, but part of it, on the other hand, is derived from a colourless augite, and a kernel of the latter mineral sometimes remains unchanged. Grains of magnetite are present, and abundant prisms of apatite (fig. 14). Mr Allport[2] noted also
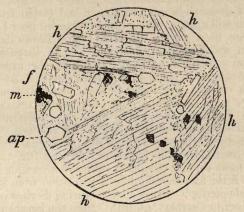
Fig. 14. Diorite, Atherstone, Warwickshire; ×20.

The figure shews idiomorphic hornblende (*h*), turbid felspar (*f*), magnetite (*m*), and rather abundant prisms of apatite (*ap*). Cross-sections of the last shew the hexagonal shape, and longitudinal sections shew the cross-fracture [1608].

olivine pseudomorphed by carbonates, *etc.* Rather coarse-grained diorites are met with in the curious complex of

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[1] G. H. Williams, *A. J. S.* (1888) xxxv, 443–445; Kemp, *ibid.* xxxvi, 247–254.

[2] *Q. J. G. S.* (1879) xxxv, 637–641. Some of the rocks included as diorites by this author would now be classed with the camptonites: see below, Chap. X.; compare Watts, *Pr. Geol. Ass.* (1893) xv, 394–396.

igneous rocks in the Malvern district. A specimen taken near the New Reservoir consists essentially of idiomorphic greenish-brown hornblende and labradorite felspar. The latter shews albite- and pericline-lamellation, and its decomposition has given rise to zeolites and paragonite mica. In the well-known diorite of Brazil Wood[1] in Charnwood Forest, Leicestershire, the hornblende tends to embrace the felspar, and this departure from the granitic type of structure is observable in some other diorites from the Midland counties.

Various diorites occur in the interior of Anglesey. One between Gwindu and Llanfaelog is a coarse-textured rock consisting of greenish-brown hornblende and turbid felspar with magnetite and apatite. The minor intrusions near Llanerchymedd[2] are of a rather different type. Brown hornblende occurs in well-formed crystals and also in shapeless plates, which can sometimes be seen forming at the expense of a colourless augite. There is also hornblende of later growth than the crystals mentioned but not derived from augite. It occurs as a crystalline outgrowth of the original brown crystals. Part of it has grown upon the clinopinacoid faces and itself shews crystal boundaries; this is green. Part has grown chiefly on the terminations of the original crystals and filled-up interstices : this is pale or colourless (fig. 13). Some of these rocks contain olivine, or rather its alteration-products, and but little felspar, affording a transition from diorite to hornblende-picrite[3]. Other olivine-bearing diorites occur near Clynog-fawr in Caernarvonshire[4]. Here the hornblende forms ophitic plates and is probably in part derived from augite. The same remark applies to certain rocks at Penarfynydd[5] in the Lleyn peninsula, where both ophitic and idiomorphic augite may be seen partly converted into brown hornblende. Olivine seems to have been rare in these latter rocks, but they are closely associated with a hornblende-picrite rich in that

[1] Hill and Bonney, *Q. J. G. S.* (1878) xxxiv, 224.

[2] *G. M.* 1887, 546–552. Other types of dioritic rocks from Central Anglesey are described by Mr Blake, *Rep. Brit. Assoc.* for 1888, 403–406.

[3] Bonney, *Q. J. G. S.* (1881) xxxvii, 137–139; (1883) xxxix, 254–256.

[4] *Bala Volc. Ser. Caern.* 102–106.

[5] *Ibid.* 92–97.

mineral. Some thoroughly basic dioritic rocks, very like those of Anglesey, occur in the Lake District, *e.g.* at Little Knott[1], White Hause, and Great Cockup[2] in the Skiddaw district. The rock at the first-named locality shews beautifully the pale fringes of hornblende which form a crystalline outgrowth of the original idiomorphic crystals. These fringes are clearly secondary, and occupy the place of destroyed felspar, *etc.* Some olivine has been present in some specimens. These Welsh and Cumbrian dioritic rocks occur usually in small laccolitic intrusions, probably of Ordovician age.

In the Isle of Man several small masses of diorite are found on Langness. The hornblende, of a greenish-brown tint, is perfectly idiomorphic, but often shews secondary outgrowths. The felspars are much decomposed. Abundant zoisite, epidote, calcite, *etc.*, have been produced, and the quartz which is always found is probably all secondary. Apatite is plentiful, but a little pyrites is usually the only iron-ore present.

The diorites of the Scottish Highlands are not yet described in any detail. Those of the Garabal Hill district include mica-diorite and augite-diorite. The pale green augite is usually in allotriomorphic grains irregularly bordered by green hornblende. Diorites, with other hornblendic rocks, occur near Inchnadamff in Sutherland[3]. Here the hornblende is in unusually perfect crystals.

In America the Cortlandt rocks include diorites consisting of brown hornblende, andesine, apatite, and magnetite, sometimes with accessory hypersthene, and by failure of the felspar these rocks graduate into hornblende-rocks. There are also diorites with green hornblende[4]. From Alabama[5] are described both basic diorites and others of more acid nature, which contain a little quartz and orthoclase. The diorites described

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[1] Bonney, *Q. J. G. S.* (1885) xli, 511–513, pl. xvi, fig. 2.
[2] Postlethwaite, *Q. J. G. S.* (1892) xlviii, 510.
[3] Teall, *G. M.* 1886, 346–353.
[4] G. H. Williams, *A. J. S.* (1888) xxxv, 441, 442.
[5] Clements, *Bull. No. 5 Geol. Sur. Ala.* (1896) 152–165; Brooks, *ibid.* 189, 190.

by Zirkel[1] from Nevada are chiefly of the more acid kind,
sometimes carrying quartz or, again, passing into mica-diorite
(Pah-Ute range). The diorites of the great laccolitic masses
in Colorado, Utah, and Arizona, of which Cross[2] has given a
full account, are also of relatively acid varieties, with quartz,
and tend to take on a porphyritic structure, graduating into
quartz-porphyrites.

A number of dioritic rocks may be studied in the Channel
Islands. A very fresh rock from the quarries of Delancy Hill,
Guernsey, is an *augite-diorite*, with colourless augite as well as
brown original hornblende. The latter mineral is moulded on
the felspar-prisms, and often borders the augite with the usual
crystallographic relation (fig. 15). A specimen from Rope-
walk Quarry is also an augite-diorite with diabasic characters.
The colourless augite is partly in rounded grains enclosed by
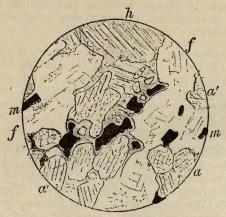
FIG. 15. AUGITE-DIORITE, DELANCY HILL, GUERNSEY; × 20.

The augite shews either sharp octagonal cross-sections (*a*) or more
rounded contours (*a'*). Hornblende (*h*), magnetite (*m*), and clear plagio-
clase felspar (*f*) are the other constituents. Much of the hornblende
occurs in marginal intergrowth with the augite, interposed between the
latter mineral and the magnetite [431].

[1] *Micro. Petrogr. Fortieth Parallel* (1876), 85–93.
[2] *Laccolitic Mountain Groups*, 14th *Ann. Rep. U. S. Geol. Sur.* (1895).

the felspar, partly in shapeless plates, and the brown horn-
blende, apparently an original mineral, is clearly of posterior
consolidation to the felspar. Magnetite is plentiful, and there
are some large crystals of a rhombic pyroxene replaced by
bastite. An augite-diorite from Fort Touraille, in Alderney,
gives evidence of the conversion of augite into hornblende.
Some deep brown biotite is also present, and a little interstitial
quartz is the last product of consolidation.

The *essexite* of Sears[1], occurring in association with the
nepheline-syenite of Salem, Mass., may be regarded as a
peculiar olivine-augite-diorite allied to the theralites. The
pale green augite is bordered by brownish hornblende, and
brown biotite is intimately associated with them. The rounded
grains of olivine are often pseudomorphed by biotite-aggregates,
green hornblende, and granular augite. The iron-ore is tita-
niferous, and gives rise to secondary sphene. Apatite is
abundant in irregular grains as well as in slender prisms.
The felspar, in idiomorphic crystals, is chiefly an acid labra-
dorite, but a subordinate amount of alkali-felspar is also
present, and perhaps some nepheline. A similar rock is
found at Mount Royal and other places near Montreal[2].
Here the augite is of a reddish-violet colour, probably tita-
niferous. The rock passes into a theralite carrying both
nepheline and sodalite. An essexite has been described from
the Rosita Hills, Colorado[3]. Brögger's rock from Gran, in the
Christiania basin, is similar. Here hornblende is wanting,
the dominant coloured silicate being a violet titaniferous
augite[4].

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[1] *Bull. Essex Inst.* (1891) xxiii : see also Washington, *Journ. Geol.*
(1899) vii, 52–64.
[2] Dresser, *Amer. Geol.* (1901) xxviii, 205, 206 (Shefford Mt.).
[3] Cross, *Proc. Colo. Sci. Soc.* (1887) 246, 247.
[4] *Q. J. G. S.* (1894) l, 18.

CHAPTER V.

GABBROS AND NORITES.

THE gabbros and their allies are holocrystalline rocks, typically of plutonic habit, in which the essential constituents are a lime-soda-felspar and a pyroxene. Of intermediate to thoroughly basic character, they correspond partly with the diorites ; but the more acid, and especially the quartz-bearing types, are less represented in the pyroxenic than in the hornblendic series. According to the dominant pyroxene, we recognize *gabbro*[1] proper (euphotide of Haüy) with diallage or augite, and *norite* (also called hypersthenite[2]) with a rhombic pyroxene. A few of the more acid rocks contain free silica (*quartz-gabbro* and *quartz-norite*). In most of the more basic varieties olivine becomes a characteristic mineral (*olivine-gabbro* and *olivine-norite*). The majority of the rocks in this family contain more or less olivine, and the mineral may be present or absent in different specimens of the same mass.

The gabbros and norites, indeed, shew considerable variations in mineralogical constitution in parts of one mass, and most of the special types are probably to be regarded as merely local modifications. Thus, by the failure of one or other of the chief constituents of a gabbro we may have an almost pure *felspar-rock* (labrador-rock, anorthosite) or *pyroxene-rock*

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[1] Gabbros in which the felspathic element is anorthite have sometimes been termed eucrite.

[2] In many of the 'hypersthenites' of the older writers the supposed hypersthene is only a highly schillerized diallage.

(diallage-rock, *etc.*, 'pyroxenite' of Williams[1]). By the disappearance of pyroxene in an olivine-gabbro we have the so-called *troctolite* (Ger. Forellenstein), composed essentially of felspar and olivine : with abundant olivine and diminishing felspar we have transitions to the succeeding family of peridotites.

The name *hornblende-gabbro* has been used for rocks of this family which contain hornblende in addition to pyroxene, or in which original pyroxene is more or less completely replaced by hornblende[2]. When the conversion is complete we have no decisive criterion for verifying the derivative nature of the hornblende, and, as already remarked, the distinction between diorite and gabbro is a somewhat artificial one[3].

A historical account of the classification of the gabbros and allied rocks has been given by Bayley[4].

Constituent minerals. The felspar of the gabbros and norites ranges in different examples usually from *labradorite* to *anorthite*. It builds large irregularly-shaped plates with, as a rule, rather broad lamellæ[5] (albite twinning) often crossed by fine pericline-striation. The lamellæ not infrequently have something of a wedge-shape[6]. A crystal with broad albite lamellæ, if cut nearly parallel to the brachypinacoid, may appear untwinned. It is not safe to assume that the most constant twin-lamellation necessarily corresponds with the albite law : the felspar of some rocks of this family has pericline twinning alone or predominant.

Zonary structure is typically not found. Besides fluid-pores and inclusions of earlier products of crystallization, the felspars often shew more or less marked schiller-structure[7]

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[1] *Amer. Geol.* (1890) vi, 40–49. Williams regarded the pyroxenites as a group coordinate with the peridotites. The name is ill-chosen, having been employed in two or three other quite different senses.

[2] R. D. Irving, *Copper-bearing Rocks, L. Superior,* 56–58, pl. VII.

[3] Prof. Cole restricts the name gabbro to the olivine-bearing (corresponding roughly to the basic) division, and styles the intermediate felspar-augite-rocks 'augite-diorite.'

[4] *Journ. Geol.* (1893) i, 435–456.

[5] Cohen (3), pl. XXV, fig. 3.   [6] *Ibid.* pl. XXVI, fig. 2.

[7] *Ibid.* pl. V, fig. 2.

(fig. 1, *g*). The modes of alteration of the felspars are various : Rosenbusch notes the curious fact that calcite is seldom formed. The 'saussurite' change seems to belong often to dynamic metamorphism rather than to weathering (see below, Chap. XXI.). Any plagioclase more acid than labradorite is exceptional, and so is the occurrence of *orthoclase* (*e.g.* Carrock Fell and Lake Superior region[1]).

The *augite* of the gabbros builds irregular crystal-plates and wedges of very pale green or light brown colour. Besides the usual prismatic cleavage, an orthopinacoidal cleavage and *diallage*-structure are very common[2]. Instead of this, there is sometimes a very minute striation parallel to the basal plane. The common twin, parallel to the orthopinacoid, is often associated with this (fig. 16, *A*). Decomposition gives
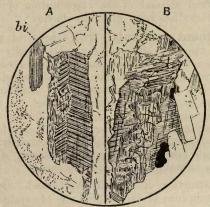
FIG. 16.   PYROXENES IN THE GABBRO OF CARROCK FELL, CUMBERLAND ; × 20.

The dominant variety is an augite with basal striation. *A* shews this structure combined with twinning on the orthopinacoid to give the 'herring-bone' structure. The mineral is partly converted to green hornblende [1870]. *B* shews a parallel intergrowth of the augite with enstatite, the latter mineral forming the core and the former the outer shell, but with detached portions of augite enclosed in the enstatite in micrographic fashion [2279].

[1] R. D. Irving, *Copper-bearing Rocks of L. Superior*, 50–55, pls. v, vi.
[2] Cohen (3), pl. xlii, fig. 3.

a scaly or fibrous aggregate of chlorite and serpentine with other products. Another common alteration is the conversion to hornblende[1], which may be light green and fibrous (uralite) or deep brown and compact.

The rhombic pyroxenes, *bronzite* and *hypersthene*, occur as accessory minerals in rather rounded but allotriomorphic crystals, while in the norites they often shew but little crystal-outline. A schiller-structure[2] is common in many norites and gabbros (fig. 17). The most usual alteration is into distinct pseudomorphs of the serpentinous mineral bastite. This is pale green or yellowish with slight pleochroism and low polarization-tints. The pseudomorph is built of little fibres arranged longitudinally, and is traversed by irregular cracks
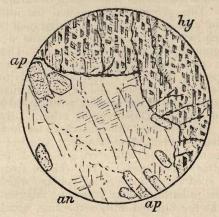
Fig. 17.   Norite (hypersthenite), coast of Labrador ; ×20.

Consisting of hypersthene (*hy*), felspar (*an*), and apatite (*ap*). Schiller-inclusions are strongly developed in the hypersthene and to a less extent in the felspar [G 444].

which the fibres do not cross (see fig. 23). The individual fibres give straight extinction, but, as there is a slight

[1] See G. H. Williams, *A. J. S.* (1884) xxviii, 261–264 ; *Bull. No.* 28 *U. S. Geol. Sur.* (1886).
[2] Cohen (3), pl. v, fig. 3.

departure from perfect parallelism in their arrangement, a very characteristic appearance is offered. The rhombic pyroxenes also shew uralitization.

In the rocks here included original *hornblende* is found only as an occasional accessory: a deep brown variety occurs in some norites. Brown *biotite* may also occur as a minor accessory (*e.g.* Carrock Fell; St David's Head), and it may be intergrown with augite (Stanner Rock, near New Radnor[1]).

When *olivine* is present, it builds imperfect crystals or rounded grains, colourless in slices. Where it adjoins felspar, it is often bordered by a rim of hypersthene. The olivine sometimes has schiller-inclusions.

The characteristic mode of alteration of olivine is 'serpentinization.' This process begins round the margin of the crystal-grain and along the usually irregular network of cracks which traverses it. Along these, as a first stage, strings of granular magnetite separate out. The immediate walls of the cracks are converted into pale greenish or yellowish fibrous serpentine, the fibres set perpendicularly to the crack, and giving straight extinction and low polarization-tints. At this stage the meshes of the network are occupied by unaltered remnants of olivine. These may be subsequently altered to serpentine, which is of a different character from that first formed, being often sensibly isotropic[2]. As a last stage, some of the magnetite may be reabsorbed, giving a deeper colour to the serpentine pseudomorph. The change from olivine to serpentine involves an increase of volume, which gives rise to numerous radiating cracks traversing adjacent minerals[3]. These cracks are injected with serpentine, usually isotropic (fig. 18).

Where original *quartz* occurs in gabbros, *etc.*, it has the same properties as that in granites. Usually it forms part of a micrographic intergrowth.

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[1] Cole, *G. M.* 1886, p. 221, fig. 3.
[2] This effect is possibly due to the overlapping of a crowd of minute fibres or scales without any definite orientation. For successive stages of serpentinization of olivine see Cohen (3), pl. LIX.
[3] Cohen (3), pl. LXXVII, fig. 4.

Original iron-ores occur only sparingly in some rocks of the gabbro family, but sometimes become abundant. They are *ilmenite* (with leucoxene as a decomposition-product) and *magnetite*. In some cases brown grains of *picotite* are found.
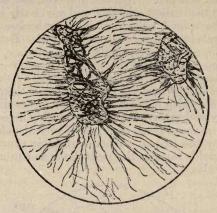

FIG. 18. LABRADORITE-OLIVINE-ROCK (TROCTOLITE), COVERACK COVE, CORNWALL ; ×20.

The olivine is almost wholly converted into serpentine (a few clear granules remaining), and the consequent expansion has caused radiating fissures through the surrounding felspar [1116].

The *apatite* builds the usual hexagonal prisms or sometimes short rounded grains (fig. 17). In other accessories the rocks are usually very poor, zircon and original sphene being absent.

Structure. In texture the rocks of this family vary from medium to coarse grain. In some the individual crystals of felspar and pyroxene attain a large size, and they are then, as a rule, strongly affected by schiller-structures. Porphyritic structure is very rarely met with in the gabbros and norites.

The order of crystallization is in general less decisively marked in basic than in acid rocks. This seems to be due to the periods of crystallization of the several minerals having in

great measure overlapped. The relative idiomorphism of the crystals only indicates the order in which they *ceased* to form, not that in which they began. It is only with this understanding that the rocks of the gabbro family can be said to follow the normal law. Apatite, iron-ores, and olivine, when present, are the earliest minerals, and are clearly idiomorphic, while in the special types containing orthoclase and quartz these minerals have always crystallized last. But as regards the two main constituents, augite and plagioclase, the mutual relations are not always the same. In many gabbros the felspar is more or less distinctly embraced by the augite or diallage, but if this character becomes marked there are always other features which indicate a transition to the diabase type. The more typical gabbros are often thoroughly hypidiomorphic; or the augitic constituent, especially if very abundant, may be embraced by the felspar. When a rhombic pyroxene enters, it is idiomorphic towards the monoclinic, and usually towards the felspar also.
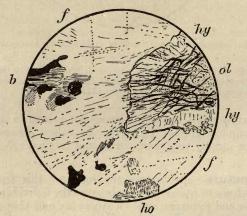
FIG. 19. OLIVINE-NORITE WITH CORONA-STRUCTURE, SEILAND, NEAR HAMMERFEST; ×15.

A much-fissured crystal of olivine (*ol*) is surrounded by a continuous ring of hypersthene (*hy*) interposed between it and the anorthite felspar (*f*). There is a little brown hornblende (*ho*) and some brown biotite (*b*) clinging about the iron-ore grains [418].

In many plutonic rocks there is an evident tendency for the earlier formed minerals to serve as nuclei round which the later ones have crystallized. This tendency is most marked in basic and ultrabasic rocks. Thus in gabbros and norites the pyroxenes often form a more or less continuous ring or '*corona*' round olivine or iron-ores (fig. 19). This is the 'celyphytic structure' of Rosenbusch. Bayley[1], while noting this feature, further describes fibrous intergrowths of felspar and augite surrounding olivine or magnetite. These seem to be original, but in other cases there is reason to believe that a mineral bordering another one is of secondary origin. Good examples are figured and described by G. H. Williams[2] in the hypersthene-gabbros of the Baltimore district. Here both hypersthene and diallage are surrounded by a double '*reaction-rim*' of hornblende, interposed between the pyroxene and the felspar and due to a reaction between them. The inner zone of the rim is of fibrous, the outer of compact hornblende. They are apparently the beginning of a process by which the pyroxenes are eventually wholly transformed into green hornblende, and the author named considers that they do not necessarily imply dynamic metamorphism. In many cases there seems to be no decisive evidence as to the primary or secondary origin of the interposed minerals.

Gabbros with granulitic structure occur in many districts, sometimes in intimate association with those of more normal type. Most of the rocks styled pyroxene-granulites probably fall under this head, but we defer noticing these until a later chapter (Chap. XXII.).

Leading types. We begin with the rather exceptional rocks in which free silica has been developed as an original constituent. A good example of a *quartz-gabbro* is that of Carrock Fell, in Cumberland[3]. It consists mainly of a somewhat basic labradorite and an augite with basal striation.

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[1] *Amer. Journ. Sci.* (1892) xliii, 515–518; *Journ. of Geol.* (1893) i, 702–710.

[2] *Bull. No.* 28, *U. S. Geol. Sur.* (1886), with plates.

[3] *Q. J. G. S.* (1894) l, 316–318, pl. xvii : (1895) li, 125. The rock has been termed hypersthenite, but the rhombic pyroxene is always subordinate to the monoclinic and sometimes wanting.

Imperfect prisms of enstatite also occur, and there is often a parallel intergrowth of the two pyroxenes (fig. 16, *B*). The augite is often converted into a greenish fibrous hornblende and the enstatite into bastite. Biotite is found locally. Magnetite and ilmenite occur, sometimes in evident intergrowths. Quartz is found partly in interstitial grains but chiefly in micrographic intergrowth with felspar, some of which is orthoclase. The rock varies much, the central part of the mass being rich in quartz, while the margin is highly basic, free from quartz and remarkably rich in iron-ores and apatite. The mutual relations of the felspar and augite vary, but on the whole the augite tends to envelope the felspar. Specimens of the gabbro of St David's Head, also intrusive in Lower Palæozoic strata, are identical with the rock just described, except that the highly basic modification is not found. Biotite is rather more plentiful, and the quartz and micropegmatite occur rather more sparingly. The rhombic pyroxene is represented by pseudomorphs of pleochroic green bastite, always abundant.

Hypersthene-bearing quartz-gabbros are extensively developed near Wilmington, Delaware[1]. Some varieties have biotite, and by increase in the proportion of this mineral pass into the type which Chester styles ' gabbro-granite.' In other varieties brown hornblende becomes a conspicuous mineral, but this is probably formed at the expense of the diallage.

The well-known rocks of the Lizard district[2] in Cornwall are, for the most part, simple *gabbros* without olivine, although that mineral occurs in some varieties. Judging from the cases in which precise determinations have been made, the felspar seems to be labradorite in the less basic rocks, anorthite in the most basic. It shews broad albite-lamellæ, often crossed by others following the pericline law. The pyroxene varies from a pale green diopside, almost colourless in slices, to typical diallage, the diallagic structure being often seen to affect only part of a crystal. The enstatite-group is wanting

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[1] Chester, *Bull. No.* 59, *U. S. Geol. Sur.* (1890).
[2] Teall, *G. M.* 1886, 483–485. For description of particular varieties see Bonney, *Q. J. G. S.* (1877) xxxiii, 884–915, and other papers.

or rare. When olivine occurs it builds colourless grains, shewing various stages of serpentinization.

The Lizard gabbros exhibit, however, numerous modifications which are ascribed to dynamic metamorphism, especially the conversion of the felspar to 'saussurite' and of the augite to amphibole. The minutely granular mineral-aggregate known as saussurite is opaque in any but the thinnest slices, and can be studied only under high magnifying powers. The change may be seen to begin in spots in the felspar crystals and spread to the whole. The pyroxene passes over into uralitic or actinolitic or compact hornblende in different cases[1], the secondary amphibole being pale green or brown or colourless, or sometimes having a bright emerald-green colour (smaragdite). According as one or both of these changes have affected the original felspar-pyroxene-rock, we have saussurite-diallage-gabbro, felspar-hornblende-gabbro, or saussurite-hornblende-gabbro. At Karakclews occurs a rock consisting of a fine-grained aggregate of augite (malacolite), labradorite, sphene, and an unknown substance, brown by transmitted and white by reflected light. Mr Teall[2] states that much of the so-called saussurite of the Lizard is similar to this rock in composition. Another mineral considered to be of secondary origin is the rhombic amphibole anthophyllite[3]. This sometimes occurs in colourless and rather fibrous crystals, forming a zone round grains of altered olivine, and surrounded in turn by an outer zone of green actinolite.

Gabbros without olivine are met with in Canada, New Hampshire, and other parts of America. Some from the north-western part of the Adirondacks, N.Y.[4], consist essentially of felspar, in general labradorite, and augite, often transformed to compact hornblende. Usually the ferro-magnesian mineral predominates, but there are rapid transitions to a highly felspathic type. Other gabbros in the same district have accessory hypersthene. Gabbros without, as well as others with, olivine are largely developed in the Lake Superior region and the neighbouring parts of Minnesota,

[1] Teall, pl. xviii, fig. 2.
[2] M. M. (1888) viii, 118.
[3] Teall, ibid. 119.
[4] Smyth, Bull. Geol. Soc. Amer. (1895) vi, 263–284.

Wisconsin, *etc.*[1]   An interesting type is the *orthoclase-gabbro*
of Irving[2], in which the plagioclase felspar is oligoclase or
an allied variety, and some orthoclase occurs in addition.
The augite may be diallagic and is often uralitized ; apatite
is abundant ; and the iron-ore is a highly titaniferous mag-
netite (Duluth and Lester River, Minn., *etc.*).

Among rocks which have been styled *hornblende-gabbro*,
some examples from Guernsey (Bellegrève) exhibit very
beautifully the conversion of colourless augite into brown
or greenish-brown compact hornblende, the process being
seen in every stage.   In some slides no augite remains, and,
without comparison with other specimens, the rock might
be taken for a true diorite, but the hornblende is probably
all derivative.   The ferro-magnesian silicates are often moulded
on the felspar, which is of a basic variety.   Magnetite and
apatite are the only other constituents.

Another good illustration is furnished by the rocks styled
' gabbro-diorite ' by Williams in the Baltimore district[3].   These
have been originally hypersthene-bearing gabbro, and the
transformation of both pyroxenes into green hornblende, fibrous
or compact, can be traced step by step.   The process is equally
well displayed in some of the Cortlandt norites[4].   A good
hornblende-gabbro, with compact brown hornblende, occurs
near Bad River, Wisconsin[5].

The Tertiary igneous rocks of the Inner Hebrides (Skye,
Rum, Mull, *etc.*) include numerous *olivine-gabbros*, and accord-
ing to Prof. Judd[6] most of the gabbros there carry olivine,
though that mineral may be obscured by secondary magnetite.
The augite, as a rule, has a striation parallel either to the
basal plane or to the orthopinacoid, with more or less marked
schillerization ; but the author named has shewn how in

[1] Wadsworth, *Prelim. Descr. of the Perid., Gabbros, etc., of Minn.*
(1887) ; R. D. Irving, *Copper-bearing Rocks of L. Superior, Monog. No. 5
U. S. Geol. Sur.* (1884).

[2] R. D. Irving, *l. c.* 50–56, pls. v, vi.

[3] *Bull. No. 28, U. S. Geol. Sur.* (1886) with plates : *abstr.* in *G. M.*
1887, 87, 88.

[4] G. H. Williams, *A. J. S.* (1884) xxviii, 261–264, with figures.

[5] R. D. Irving, *l. c.* 56–58, pl. vii, figs. 1–3.

[6] *Q. J. G. S.* (1886) xlii, 49–89, pl. iv.

the more deep-seated portions of the large rock-masses schiller-structures come in in more than one direction, and affect the felspar and olivine as well as the pyroxene. A rhombic pyroxene is only locally present. The olivine is often of a variety rich in iron, and gives rise to much magnetite-dust as an alteration-product. Original iron-ores and apatite may or may not be present. The felspar is usually a labradorite, and this, rather than the pyroxene, tends to assume crystal outlines, the structure of the rock being often ophitic, and the gabbro graduating into diabase.

Very similar to the Scottish Tertiary gabbros are those of the Carlingford district in Ireland, probably of like age. Prof. von Lasaulx[1] described specimens consisting of anorthite, diallage, and olivine. These were from Slieve Foy. From the neighbouring hill of Barnavarve Prof. Sollas[2] describes a gabbro free from olivine, consisting of a basic felspar (anorthite or bytownite) with rhombic and monoclinic pyroxenes, which shew rather remarkable intergrowths. Here is also a variety of the rock containing interstitial micro-pegmatite, which the author named believes to be due to a later injection.

Among American olivine-gabbros[3] those described by Irving[4] from the Lake Superior region tend to the ophitic type of structure. The felspar is usually anorthite or some other basic variety; the augite sometimes, but not always, shews the diallage character; the iron-ore, often in large grains, is magnetite only slightly titaniferous; and apatite is rare. A rock from Pigeon Point, Minn.[5], consists of fresh labradorite, purplish pink titaniferous augite, olivine, titaniferous magnetite, and a little apatite. One modification contains large porphyritic crystals of the felspar. The large gabbro mass at the base of the Keweenaw formation in north-eastern Minnesota[6] consists essentially of a basic labradorite, augite, an olivine rich in iron (hyalosiderite),

[1] *Sci. Proc. Roy. Dubl. Soc.* (1878) ii, 31–33.
[2] *Tr. Roy. Ir. Acad.* (1894) xxx, 482–487.
[3] For coloured plate of example from New Hampshire see Berwerth, Lief. II.
[4] *Copper-bearing Rocks of L. Superior* (1884), with coloured plates.
[5] Bayley, *Bull. No.* 109, *U. S. Geol. Sur.* (1893) 32–38, pl. v.
[6] Bayley, *Journ. of Geol.* (1893) i, 696–714.

and a non-titaniferous magnetite; but wide differences in the relative proportions of these constituents give rise to numerous varietal forms.

As already intimated, many of the rocks in this family contain both augite (or diallage) and hypersthene in varying proportions, and no hard line is to be drawn between gabbros and norites. In Sweden the rocks termed 'hyperite' by Törnebohm vary between olivine-gabbro and norite, olivine and hypersthene appearing to replace one another, so that the total of the two remains about the same in the different varieties. The same thing is seen in the north of Norway and elsewhere. It is convenient to restrict the name norite to rocks in which the sole or dominant pyroxene is of a rhombic variety, those in which the rhombic is only subordinate to the monoclinic pyroxene being termed *hypersthene-gabbro*. Such rocks are represented sparingly among the gabbros of Skye and Mull. They occur also in the Baltimore district[1], in the Adirondacks[2], in Alabama[3], *etc.* An orthoclase-bearing variety comes from Emigrant Gap, Placer Co., Cal.[4]

A good example of *quartz-norite* is described by Grant[5] from Mount Hope, near Baltimore. It consists of bytownite, quartz, and hypersthene, with accessory magnetite and apatite, and has a granitoid structure.

A well-known example of *norite* comes from the island Hitterö, off the west coast of Norway. The rhombic pyroxene is a hypersthene rich in iron; but, as is often the case, the ferriferous ingredient is concentrated in numerous deep brown schiller-inclusions, leaving the general mass of the crystal pale and scarcely pleochroic. Some specimens have a considerable amount of iron-ore (probably titaniferous) surrounded by green hornblende.

[1] G. H. Williams, *Bull. No.* 28, *U. S. Geol. Sur.* (1886).

[2] C. H. Smyth, jr., *A. J. S.* (1894) xlviii, 54–65; *Bull. Geol. Soc. Amer.* (1895) vi, 271.

[3] J. M. Clements, *Bull. No.* 5, *Geol. Sur. Ala.* (1896) 171, 172.

[4] Lindgren, *Bull. No.* 148, *U. S. Geol. Sur.* (1897) 212.

[5] *Joh. Hopk. Univ. Circ.* (1893) xii, 48.

In Scotland norites occur in Aberdeenshire, Banffshire, and other districts. One from Towie Wood, near Ellon, consists essentially of labradorite and a rhombic pyroxene, which is pale and without schiller-structure (enstatite); while others from the same neighbourhood contain in addition augite, hornblende, and biotite.

A well-known American example, with strongly schillerized hypersthene, comes from the coast of Labrador[1] (fig. 17). Patches of brown hornblende and biotite are sometimes intergrown with the hypersthene. In places it becomes bleached, with a separation of granular magnetite. The other main constituent is felspar (usually typical labradorite but sometimes a more basic variety), moulded on the imperfect crystals of hypersthene. Stout prisms of apatite also occur, and sometimes patches of iron-ore bordered by brown mica. Norites are found also in the Sudbury district of Canada and at several localities in the north-eastern part of the United States. From the Adirondacks Kemp[2] describes rocks composed essentially of augite, hornblende, hypersthene, and felspar. Norites and allied types are included among the Cortlandt rocks on the Hudson River[3]. The norite proper consists mainly of andesine and hypersthene, both with schiller-inclusions. There is accessory biotite, and a remarkable feature is the occurrence of large crystals of orthoclase enclosing the other minerals in 'pœcilitic' fashion. In other rock-types from this district the hypersthene is associated with green or brown hornblende (hornblende-norite), with biotite and magnetite (mica-norite), or with augite and biotite (augite-norite).

In this place may be included the rocks to which Rosenbusch has given the name *theralite*, and which may be considered as nepheline-gabbros. The original type is from the Crazy Mts in Montana[4]. Here olivine is only an occasional accessory.

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[1] Cohen (3), pl. v, fig. 3.

[2] 19*th Ann. Rep. U. S. Geol. Sur.* (1899) part III, pl. LX, *A*.

[3] G. H. Williams, *A. J. S.* (1887) xxxiii, 135–144, 191–194.

[4] Wolff, *Notes on the Petrography of the Crazy Mts, etc., Northern Transcontinental Survey* (1885); and in Diller, 197–200. For coloured plate see Berwerth, Lief. II.

Hornblende is not present in the typical rock, but the idiomorphic augite, pale green to almost colourless in slices, is often surrounded by a narrow border of deep green pleochroic ægirine. The felspar is partly unstriated plagioclase, partly perhaps anorthoclase. It forms with nepheline a granular aggregate, in which either mineral may be idiomorphic towards the other. The remaining constituents are biotite, apatite, and a little iron ore, with sometimes sodalite (Rock Creek) or haüyne (Martinsdale). A purer theralite is described from Costa Rica[1]. This consists of augite, labradorite and a little orthoclase, nepheline and a mineral of the sodalite group, biotite, apatite, and magnetite, with secondary zeolites.

A more remarkable rock is Pirsson's *missourite*[2] from the Highwood Mts, Montana, a leucite-gabbro, corresponding with the volcanic leucite-basalts. It is quite devoid of felspar, consisting of olivine, augite, biotite, and leucite, with some apatite and iron-ore. The structure is thoroughly allotriomorphic.

The *felspar-rocks* known in America as anorthosite must be regarded as peculiar members of the gabbro family. Such rocks, of pre-Cambrian age, occupy extensive tracts in Minnesota[3], *etc.*, near Lake Superior. The felspar which makes up almost the whole of these coarse-textured aggregates varies from labradorite to anorthite in different localities[4]. A little augite, of faint violet-brown tint in sections, is the only other original mineral, and this occurs both in grains and as minute parallel interpositions in the felspar. Similar rocks have been described by Adams in the so-called Norian of several districts in Canada, by Kemp[5] in the Adirondacks, *etc.*

[1] Wolff, *A. J. S.* (1896) i, 271, 272.
[2] *A. J. S.* (1896) ii, 317–323.
[3] R. D. Irving, *Copper-bearing Rocks of L. Superior*, 59–61, pl. VII, fig. 4; Lawson, *Bull. No.* 8, *Geol. and Nat. Hist. Sur. Minn.* (1893) and *abstr.* in *M. M.* x, 263. The very coarse-textured felspar-rock of Labrador, with its beautiful schiller-structure, is in all mineralogical collections.
[4] The mineralogical term 'anorthose' (Delesse), from which anorthosite is named, is synonymous not with anorthite but with plagioclase generally.
[5] *Bull. Geol. Soc. Amer.* (1894) v, 215, 216; *Geology of Moriah and Westport, Bull. N.Y. State Mus.* (1895) iii, 337.

In our country gabbros pass only locally into labradorite-rocks by the failure of the pyroxenic constituent (Lenkeilden Cove at the Lizard, Athenree in Tyrone[1]).

. Contrasted with these are the pure *pyroxene-rocks* to which Williams in America has given the name ' pyroxenite.' The Webster type[2] is described from North Carolina and Maryland, and consists of a rhombic and a monoclinic pyroxene forming an even-grained crystalline aggregate. It is in fact a bronzite-diopside-rock. Another example, from Montana[3], consists of light green diallage and colourless enstatite with some brown mica and only occasional felspar. From the same district comes a hypersthene-hornblende-rock, sometimes rich in green pleonaste ; while rocks composed essentially of augite and hornblende have been recorded from Alabama[4] and from Mariposa Co., Cal.[5] Among other types consisting wholly of ferro-magnesian silicates we may mention a hypersthene-biotite-rock from Hamilton River in Labrador[6] and an enstatite-rock from the Transvaal[7]. In this country gabbros are only locally known to pass into augite- or diallage-rock (*e.g.* Lendalfoot in Ayrshire[8]).

By the dwindling and disappearance of the pyroxene, olivine-gabbros pass into *felspar-olivine-rock*, known as troctolite (Ger. Forellenstein). This consists essentially of a lime-soda-felspar, typically labradorite, with olivine, which may be more or less serpentinized. Such rocks are known in the gabbro area of the Lizard[9] (fig. 18), and in Minnesota[10] and other American districts of basic intrusions.

It has been noticed above that an ordinary gabbro may pass into a variety very rich in magnetite and ilmenite (*e.g.*

[1] Watts, *Guide*, 73.
[2] G. H. Williams, *Amer. Geol.* (1890) vi, 40–49, pl. II, fig. 2.
[3] Merrill, *Proc. U. S. Nat. Mus.* (1894) xvii, 662, 657, 658.
[4] Clements, *Bull. No. 5, Geol. Sur. Ala.* (1896) 163, 164.
[5] Turner, *A. J. S.* (1898) v, 423, 424.
[6] Ferrier, *Ann. Rep. Geol. Sur. Can.* (1896) viii, 344 L.
[7] Maskelyne, *Phil. Mag.* (1879) vii, 135, 136.
[8] Bonney, *Q. J. G. S.* (1878) xxxiv, 778–780.
[9] Teall, pl. viii, fig. 2.
[10] Wadsworth, *Prelim. Descr. Perid. Gabb. etc. Minn.* (1887) 95, pl. v.

Carrock Fell). Some gabbros and norites, in Scandinavia, in Minnesota[1], in the Adirondacks[2], *etc.*, shew very basic modifications which are almost pure *iron-ore-rocks*[3]. As a rule, they are highly titaniferous. An augite-magnetite-rock, consisting of crystal-grains of augite set in a framework of titaniferous magnetite, is one of the varieties of the curious banded gabbros of Skye[4].

[1] Wadsworth, *ibid.* 63, 64, pl. vi, fig. 1; Irving, *Copper-bearing Rocks of L. Superior*, 51, 52; Winchell, 10*th Ann. Rep. Minn. Geol. Sur.* (1882), 80–83.

[2] Kemp, *Bull. Geol. Soc. Amer.* (1894) v, 222.

[3] Vogt, *G. M.* 1892, 82–86 (*abstract*). For descriptions of iron-ore-rocks from Cumberland in Rhode Is. and Taberg in Sweden see Wadsworth, *Bull. Mus. Comp. Zool. Harv.* (1881) vii, 185–187; *Lith. Stud.* 75–81, pls. i, ii.

[4] Geikie and Teall, *Q. J. G. S.* (1894) l, pl. xxviii.

CHAPTER VI.

PERIDOTITES (INCLUDING SERPENTINE-ROCKS).

The peridotites are holocrystalline rocks of ultrabasic composition, in which felspar is typically absent and olivine is the most prominent constituent. They were separated from the more normal basic rocks by Rosenbusch; but, though their marked characters make it desirable to discuss them apart, they do not constitute a family comparable, *e.g.*, with that of the gabbros in importance. The peridotites do not usually occur in large bodies of uniform rock. In many localities they are seen to be only local modifications of olivine-gabbros, olivine-norites, or olivine-diorites, and they shew frequent transitions from one type to another.

For so small a' group a needless multiplicity of names has been created. The simple olivine-rock is the 'dunite' of Hochstetter. With the addition of enstatite we have the 'saxonite' of Wadsworth[1], 'harzburgite' of Rosenbusch; other types are styled 'lherzolite,' 'eulysite,' *etc.*, and the name 'picrite' is used for those characterized by augite or hornblende, usually with some felspar. For our purposes it will be sufficient to separate the *picrites*, rich in the bisilicate constituents and having usually subordinate plagioclase, from the more typical *peridotites*, very rich in olivine and non-felspathic. Different types may be specified by prefixes in the customary way (*e.g.* hornblende-picrite, enstatite-peridotite, *etc.*).

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[1] *Lithological Studies* (1884, Camb., Mass.). This work contains many descriptions of peridotites and meteorites, with a number of useful coloured plates.

Many of the meteorites ('stony meteorites' as distinguished from meteoric irons) have a mineral composition allied to that of the terrestrial peridotites, but often with special accessory minerals and peculiar structures[1].

In consequence of the unstable nature of their principal constituent mineral, the peridotites are very readily decomposed, and most of the serpentine-rocks have originated in this way.

Constituent minerals. In the typical peridotites *olivine* makes up from half to nearly the whole of the rock. If not so abundant that its crystals interfere with one another, it builds idiomorphic or rounded crystals. The mineral is colourless in thin slices, and shews either irregular cleavage-traces or a network of fissures. It often has schiller-inclusions of the nature of minute negative crystals enclosing dendritic growths of magnetite (fig. 1, *h*). Alteration along cracks gives rise to strings of magnetite granules, and complete destruction produces pseudomorphs of greenish or yellow serpentine, or sometimes colourless fibrous tremolite, *etc.*

Of the other ferro-magnesian silicates the commonest in typical peridotites is a rhombic pyroxene; either colourless or pale yellow (*enstatite*) or with faint green and rose pleochroism (*bronzite*): varieties rich in iron do not often occur. The crystals often tend to be idiomorphic. Any marked schiller-structures are not very common. Decomposition results in pseudomorphs of bastite[2]. The *augite* is either light brown to colourless, with a high extinction-angle (about 40°) as in many diabases, *etc.*, or it may shew a faint green tint (chrome-diopside). A conversion to brown hornblende is common in the picrites, and so also are parallel growths of augite and brown hornblende, the former being the kernel[3].

The *hornblende* may be a green or pale actinolitic variety, but in many of the picrites it is 'basaltic' hornblende with an extinction-angle of about 20° and colour varying from deep

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[1] See Farrington, *Journ. Geol.* (1901) ix, 51–66, 174–190, 393–408, 522–532.

[2] Fouqué and Lévy, pls. LIII, LIV.

[3] Cohen (3), pl. XXXII, fig. 1.

brown to colourless. The pale variety seems due to bleaching, often accompanied by a discharge of magnetite-dust. The *biotite* of peridotites also is frequently of a pale tint.

Some peridotites have little octahedra of *magnetite*, but some other spinellid mineral is more characteristic. It may be *chromite* (deep brown or opaque), *picotite* (coffee-brown), or *pleonaste* (green). These minerals usually build irregular rounded grains. In some of the rocks *perofskite* is a characteristic mineral, in minute crystals[1].

A basic *felspar* occurs in many of the picrites, but is wholly wanting in the more typical peridotites. Some types have accessory garnet, which is always the magnesian variety

FIG. 20. POECILITIC STRUCTURE IN HORNBLENDE-PICRITE, MYNYDD PENARFYNNYDD, CAERNARVONSHIRE; ×20.

The large plate enclosing olivine-grains and filling the field is a single crystal of hornblende. It is mostly colourless, but becomes deep brown in capriciously arranged patches round the edge [725].

pyrope, red-brown in slices. Metallic *nickeliferous iron* occurs in some of the meteoric peridotites, besides special minerals, such as troilite.

[1] *Cf.* G. H. Williams on the serpentine of Syracuse, N. Y., *A. J. S.* (1887) xxxiv, 140-142.

Structure. The constituents follow, as a rule, the normal order of crystallization, the olivine constantly preceding the bisilicates. In many picrites, and in other types not too rich in olivine, the more or less rounded crystals of olivine are enclosed by large plates of pyroxene or hornblende (*pœcilitic* structure[1], fig. 20). When felspar occurs, it is later than the pyroxenes, but in the hornblende-picrites it is often moulded in ophitic fashion by part of the hornblende.

In the most basic peridotites the largely predominant olivine builds a granular aggregate, in which may be imbedded, with a *pseudo-porphyritic* appearance, relatively large
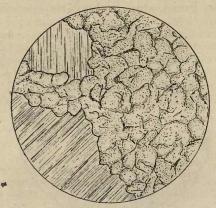
Fig. 21. ENSTATITE-PERIDOTITE WITH PSEUDO-PORPHYRITIC STRUCTURE, SKUTVIK, NEAR TROMSÖ, NORWAY; × 20.

Here olivine is largely in excess, forming a granular aggregate in which are embedded large irregular crystals of a yellowish partly altered enstatite [440].

crystals of enstatite, *etc.* (fig. 21). Any true porphyritic structure (*i.e.* some constituent occurring in two distinct generations) is rare in this family of rocks, the minerals usually forming an even-grained aggregate.

[1] This is quite analogous to the ophitic structure of diabases, *etc.* See G. H. Williams, *A. J. S.* (1886) xxxi, 30, 31; *Journ. of Geol.* (1893) i, 176.

The pyrope-bearing peridotites often shew a special type of structure, each garnet-crystal being surrounded by a broad border or shell known as *celyphite*[1] (Ger. Kelyphit). This border is sharply divided from the garnet, and possesses a marked radial fibrous structure. The name is not applied to any particular mineral, and the so-called celyphite is not always of the same constitution. A pale or colourless augite is common, while brown hornblende and enstatite are sometimes found, and brown picotite frequently accompanies the pyroxene. Again, brown biotite and magnetite have been observed[2]. A celyphite-border round garnet is also a characteristic feature in pyroxene-garnet-rocks (eclogites). Some petrologists have regarded it as a secondary 'reaction-rim,' but there seems to be no decisive reason for rejecting the primary origin of the growth.

Most of the meteoric peridotites have a peculiar structure termed *chondritic*[3]. A fine-grained matrix of olivine, enstatite, chromite, *etc.*, encloses numerous round grains (*chondri*) consisting of the same minerals. In these chondri the crystals very commonly have a tendency to diverge from a point on the circumference.

Leading types. Numerous examples of rocks rich in olivine are known from the old gneiss area of Sutherland, from the western islands of Scotland, from North Wales, Cornwall, *etc.* There are frequent transitions from felspar-bearing picrites to thoroughly ultrabasic peridotites[4].

At Penarfynnydd[5], on the south-west coast of Caernarvonshire, is an Ordovician intrusion ranging from *hornblende-picrite* to a hornblende-peridotite very rich in olivine. The hornblende is either deep brown or colourless, in the same

[1] Rosenbusch-Iddings, pl. xiv, fig. 4; Cohen (3), pl. lxi, fig. 2.

[2] Diller, *A. J. S.* (1886) xxxii, 123; *Bull. No.* 38, *U. S. Geol. Sur.* (1887) 15–17.

[3] For figures see Wadsworth's *Lithological Studies*; Lockyer, *Nature* (1890) xli, 306, 307; Farrington, *Journ. Geol.* (1901) ix, 174–180.

[4] For figures of several of these rocks, see Teall.

[5] *Q. J. G. S.* (1888) xliv, 454–457. *Bala Volc. Rocks of Caern.* 99–101. Similar rocks are recorded from Breaker Hill and Balhamie Hill in Ayrshire : see *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 469, 470, pl. xxiii, fig. 1.

crystal, and it encloses the rounded grains of olivine with
typical pœcilitic structure (fig. 20). A colourless augite
and a deep brown biotite occur, with a little original mag-
netite. Part of the hornblende is formed at the expense of
augite. Anorthite is often present, usually embraced by the
hornblende. Similar rocks occur in central Anglesey, where
secondary crystal-outgrowths from the hornblende are fre-
quent[1]. Prof. Bonney[2] has described some of these rocks,
which occur as boulders on the west coast of Anglesey. The
same writer has described from Sark[3] a somewhat different
type in which a pale altered mica is a prominent mineral,
besides pale or greenish actinolite. This seems then to be a
mica-hornblende-picrite, and Prof. Bonney compares it with
the Scye type mentioned below. G. H. Williams[4] has given
an interesting account of hornblende-picrites from the Cort-
landt district on the Hudson River. They resemble very
closely the British examples and a well-known rock from
Schriesheim, near Heidelberg[5], the bleaching of the brown
hornblende and subordinate brown biotite being a character-
istic feature. Examples from Alabama[6] have either brown
or very pale green hornblende, and contain abundant pleo-
naste. One from Montana[7] has accessory hypersthene. Prof.
Bonney[8] has described a hornblende-picrite from Swift's Creek,
Gippsland, Victoria.

An *augite-picrite* of Carboniferous age is found at Inch-
colm[9], near Edinburgh, in which the dominant coloured
mineral is a purplish-brown pleochroic augite, often with hour-
glass structure[10]. Deep brown hornblende is also present,
chiefly as a marginal intergrowth with the augite. Felspar

[1] Teall, pl. vi.
[2] *Q. J. G. S.* (1881) xxxvii, 137–140; (1883) xxxix, 254–259. Also a
similar rock from Alderney, *ibid.* (1889) xlv, 384.
[3] *G. M.* 1889, 109–112.
[4] *A. J. S.* (1886) xxxi, 31–37; and in Diller, 294–297.
[5] For coloured plate see Berwerth, *Lief.* iii.
[6] Clements, *Bull. No. 5, Geol. Sur. Ala.* (1896) 155–160.
[7] Merrill, *Proc. U. S. Nat. Mus.* (1894) xvii, 654.
[8] *M. M.* (1884) vi, 54.
[9] Cole's *Stud. Micro. Sci.* (1882) No. 6; Teall, pl. iv, fig. 2, vii.
[10] The augite resembles that of some nepheline-dolerites, and the rock
differs in other respects from true plutonic types.

and biotite are subordinate. Most of the olivine is converted into a yellow serpentine. Augite-picrites with typical pœcilitic structure occur in Shropshire[1]. Among examples from the Inner Hebrides Prof. Judd[2] notes one from the Shiant Isles with fine pœcilitic structure. Others occur in the Cuillin Hills in Skye. Busz has described an augite-picrite with comparatively fresh olivine from Highweek, near Newton Bushel, Devonshire : this has subordinate enstatite and biotite.

Intrusions of *enstatite-picrite* occur in the old gneiss of the west of Sutherland. In one near Lochinver the slightly pleochroic enstatite or bronzite is moulded on the olivine, but shews good crystal-faces, being enclosed by large crystal-plates of felspar. There is a subordinate colourless augite and some brown hornblende, which is partly formed from the pyroxenes,
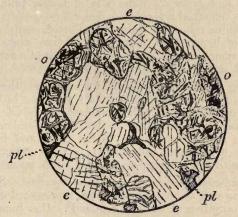
FIG. 22. ENSTATITE-PERIDOTITE, ASSYNT LODGE, SUTHERLAND ; ×20.

A granular aggregate of olivine (*o*), largely serpentinized, and a slightly pleochroic enstatite or bronzite (*e*). These two minerals are in about equal quantity ; in addition there are little irregular grains of isotropic green pleonaste (*pl*) [1642].

[1] Watts, *Rep. Brit. Ass.* for 1887, 700 ; *Proc. Geol. Ass.* (1894) xiii, 340, fig.
[2] *Q. J. G. S.* (1885) xli, 393, pl. XIII, fig. 4.

partly original and later than the felspar. This rock is almost as much a norite as a picrite, but true enstatite-peridotites also occur in the district, consisting of about equal parts of olivine and a rhombic pyroxene, with grains of pleonaste (fig. 22).

Of *mica-peridotite* few examples are described. One from Elliott County, Kentucky[1], consists of serpentinized olivine and pale yellow-brown to colourless mica, with pœcilitic arrangement, besides crystals of peroskite, *etc.* Sears[2] records a mica-peridotite from Andover in Massachussetts. Prof. Judd[3] has described under the name ' scyelite ' a *hornblende-mica-peridotite* from the borders of Sutherland and Caithness (Loch Scye and Achavarasdale Moor). Here serpentinized grains of olivine are enclosed in pœcilitic fashion by a pale green to colourless hornblende, probably pseudomorphous after diallage, and a peculiar yellow mica. A similar rock is recorded at a point $2\frac{1}{2}$ miles S. E. of Borgie Bridge. Prof. Sollas has remarked a *hornblende-hypersthene-peridotite* among the crystalline schists of Galway, at Derreennagusfoor. This consists of hypersthene, hornblende, olivine, magnetite, and a green spinel. Such rocks occur also in Custer County, Colorado[4], and in other localities[5].

Among *hornblende-peridotites* we may place the rock described as a hornblende-picrite from Greystones in Wicklow[6], which is non-felspathic. The dominant hornblende is green, and encloses in pœcilitic fashion the olivine-pseudomorphs (of magnetite and a carbonate). It has cores and borders of colourless hornblende, and there is a third variety of this mineral with few cleavage-cracks and much magnetite-dust.

Various *augite-peridotites* have been described. Specimens of these, as well as augite-picrites, are represented among the Tertiary eruptives of western Scotland[7]. One from the Isle

[1] Diller, *A. J. S.* (1892) xliv, 286–289.
[2] *Bull. Essex Inst.* (1894) xxvi.
[3] *Q. J. G. S.* (1885) xli, 401–407. Teall, pl. v, fig. 2.
[4] Cross, *Proc. Colo. Sci. Soc.* (1887) 242–244.
[5] Mánbhúm in India; see Holland, *Rec. Geol. Sur. Ind.* (1894) xxvii, 142: Kilimanjaro; see Hatch, *G. M.* 1888, 257–260.
[6] Watts, *Rep. Brit. Ass.* for 1893, 767; *Guide*, 35.
[7] Judd, *Q. J. G. S.* (1885) xli, 389–395.

of Rum shews fresh olivine set in a framework of green augite. Magnetite and chromite are accessories, and sometimes hypersthene. Others from the Cuillin Hills, Skye, consist of predominant olivine, brownish diallage, sometimes a little anorthite, and either deep brown picotite or an opaque mineral, probably chromite or chrome-magnetite. Merrill has described an augite-peridotite, from Little Deer Island, Maine[1], and a diallage-mica-peridotite from Montana[2].

A well-known *enstatite-augite-peridotite* occurs in the Pyrenees and Ariège (Lherz type)[3]. About two-thirds of the rock consists of fresh olivine, the other minerals being a colourless enstatite, a faint green to colourless chrome-bearing diopside, and irregular grains of either brown picotite or green pleonaste. As usual in types very rich in olivine, the structure is granular, not pœcilitic. Such rocks, often serpentinized, are recorded from several other districts. A porphyritic bronzite-diallage-peridotite occurs in Maryland[4], and a similar rock in Colusa County, California[5].

In some *enstatite-peridotites* the rhombic pyroxene is abundant, and forms a framework in which the somewhat rounded grains of olivine are set with pœcilitic structure. A well-known representative comes from the Harz (Baste or Harzburg type)[6], where, however, both minerals are more or less completely serpentinized. A similar rock is described from Presque Isle, Michigan[7].

In another type olivine largely predominates, and the enstatite occurs in relatively large crystals, which, among the smaller grains of olivine, give a pseudo-porphyritic appearance to the rock. Good examples occur near Tromsö, *etc.*, in

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[1] *Proc. U. S. Nat. Mus.* (1888) xi, 192–195.

[2] *Ibid.* (1894) xvii, 651, 652.

[3] See Bonney, *G. M.* 1877, 59–64, and for coloured figures Teall, pl. I, fig. 1; Fouqué and Lévy, pl. LII, fig. 1.

[4] G. H. Williams, *Amer. Geol.* (1890) vi, 38, 39, pl. II, fig. 1.

[5] Wadsworth, *Lith. Stud.* pl. v, figs. 1–3.

[6] Wadsworth, *ibid.* 133, 134, pl. VIII, figs. 1, 2, 5; Fouqué and Lévy, pl. LIII, fig. 2.

[7] Wadsworth, *Lith. Stud.* 136–138, pl. VII, figs. 3–5.

Norway (fig. 21), Inyo County, California[1], *etc.*[2] In Maryland, Williams[3] has described similar rocks in which large crystals of bronzite or diallage, or both, are embedded in a granular mass, mainly of olivine. In Montana[4] occurs a peridotite with abundant crystals of bronzite and olivine enclosed in a finely granular aggregate of enstatite, pale hornblende, some olivine, and green pleonaste.

From these rocks it is only a step to one composed wholly of olivine, with only a little accessory picotite or magnetite. Of this pure *olivine-rock* the type comes from New Zealand (Mount Dun), and is the 'dunite' of Hochstetter. In Skye very beautiful examples come from the southern part of the Cuillin Hills, near Loch Scavaig. Here the only mineral in addition to olivine is one of the spinellid group, usually deep brown picotite but sometimes green pleonaste. The picotite is in good octahedra, and in certain narrow seams becomes the principal element. In America examples of dunite come from Franklin, Webster[5], and Corundum Hill[6], all in North Carolina, and from Western Massachussetts[7].

We may class with the peridotites certain olivine-felspar-rocks which differ from the troctolites mentioned in the last chapter in having more abundant olivine and constantly anorthite as the felspathic element. Such *anorthite-peridotites* occur in Skye constantly associated with picrites, and bear the same relation to these that the troctolites do to olivine-gabbros. Here we may place rocks described by Prof. Judd[8] from Alival in the Isle of Rum and by Prof. Bonney[9] from Belhelvie in Aberdeenshire.

[1] Wadsworth, *Lith. Stud.* 132, pl. vi, fig. 4.
[2] One from New Zealand carries grains of nickel-iron alloy (awaruite), Ulrich, *Q. J. G. S.* (1890) xlvi, 625–629, pl. xxiv.
[3] *Bull. No.* 28, *U. S. Geol. Sur.* (1886) 50–55 ; *Amer. Geol.* (1890) vi, 38, 39, pl. ii, fig. 1.
[4] Merrill, *Proc. U. S. Nat. Mus.* (1894) xvii, 655.
[5] Wadsworth, *Lith. Stud.* 118, 119, pl. iv, figs. 2, 3.
[6] Chatard, *Bull.* No. 42, *U. S. Geol. Sur.* (1887) 45.
[7] Martin, *A. J. S.* (1893) vi, 244–247.
[8] *Q. J. G. S.* (1885) xli, pl. xiii, fig. 5.
[9] *G. M.* (1885) 441, 442.

Of *garnet-peridotites* that from Elliott County, Kentucky[1], is a good example. The pyrope crystals are surrounded by a 'celyphite' border of brown mica with an outer ring of magnetite-dust, these minerals being supposed to be due to a reaction between the garnet and the olivine. The serpentine-rock of Zöblitz in Saxony is another example, in which, however, the olivine is wholly destroyed. Garnet occurs as an accessory in the diallage-peridotite of Tunaberg in Norway[2] (the 'eulysite' of Erdmann) and in other localities.

Serpentine-rocks. Hitherto we have noticed only very briefly the secondary changes that affect the minerals of crystalline rocks. In the present family, however, the decomposition of a rock is often so complete that its original nature is detected only by careful study, and the altered rock-masses are commonly denoted by a special name, serpentine-rocks or simply serpentines, expressing their dominant mineral composition. The mineral serpentine is the commonest decomposition-product of the non-aluminous magnesian silicates (olivine, the rhombic pyroxenes, and some of the augites and hornblendes), and the purest serpentine-rocks result from the alteration of peridotites[3]. Other decomposition-products occur in the rocks, *viz.* iron-oxides (magnetite and limonite), steatite, carbonates (dolomite, *etc.*), chlorite, and tremolite; but the bulk is serpentine of various kinds, in which may be found undestroyed relics of the original minerals of the peridotite (olivine, diopside, pyrope, chromite, *etc.*).

Of the mineral serpentine some kinds are crystalline and doubly refracting, with the interference-colours of quartz or felspar and faint pleochroism when the green tint is sufficiently pronounced. The habit is fibrous (chrysotile) or scaly (antigorite, *etc.*). Other kinds are amorphous and

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[1] Diller, 290–294, pl. xxxix; *A. J. S.* (1886) xxxii, 121–125; *Bull.* 38 *U. S. Geol. Sur.* (1887).

[2] Wadsworth, *Lith. Stud.* 147.

[3] For descriptions of coloured figures of numerous serpentine-rocks, see Wadsworth, *Lithological Studies* (1884). For a general sketch of observations and opinions on serpentine, see Teall, Chap. vi. On serpentine from diopside, see Merrill, *Proc. U. S. Nat. Mus.* (1888) xi, 105–109, pl. xxxii; *A. J. S.* (1889) xxxvi, 189–191.

sensibly isotropic. Much of the serpentine occurs in definite pseudomorphs, and often retains something of the structure of the parent mineral to indicate its source. We may distinguish four cases :

(i) Serpentine derived from olivine, with the '*mesh-structure*[1]' (Tschermak's 'Maschenstructur'; see p. 74 and fig. 23).

(ii) Serpentine derived from enstatite or bronzite, in distinct pseudomorphs with the *bastite-structure* (see p. 73 and fig. 23).

(iii) Serpentine derived from a non-aluminous hornblende, with '*lattice-structure*[2]' ('Gitterstructur' of Weigand). Here the cleavage of the hornblende is marked by veins of birefringent serpentine in two sets making the characteristic angle $55\frac{1}{2}°$. This serpentine is minutely fibrous, with the fibres set perpendicular to the cleavage of the hornblende. The rest of the pseudomorph is of serpentine giving no definite crystalline reaction and consisting probably of a confusedly fibrous aggregate.

(iv) Serpentine derived from a non-aluminous augite, with '*knitted-structure*[3]' ('gestrickte Structur' of Hussak). This consists chiefly of serpentine with scaly habit (antigorite). The scales give straight extinction and low polarization-tints. They occur in two closely interlacing sets parallel to the cleavage-planes of the augite, and so making an angle of about 87° with one another.

The derivation of serpentine from pyroxene is very clearly exhibited in some American occurrences described by Merrill at Montville, N.J.[4] and in Essex County[5] and Warren County[6], N.Y.

The source of serpentine in rocks can often be made out by these various characters, and it is placed beyond doubt when any unaltered remnants of the parent mineral remain.

[1] Cohen (3), pl. LXII, fig. 1.
[2] *Ibid.* fig. 3.   [3] *Ibid.* fig. 4.
[4] *Proc. U. S. Nat. Mus.* (1888) xi, 105–111, pl. XXXII.
[5] *Ibid.* (1889) xii, 595–599.
[6] *A. J. S.* (1889) xxxvii, 189–191.

In addition there may be serpentine encroaching upon contiguous minerals or traversing them in veins: this is, as a rule, sensibly isotropic.
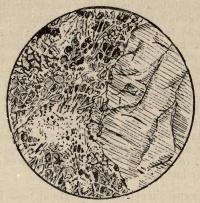
FIG. 23. SERPENTINE-ROCK, COVERACK, CORNWALL ; × 20.

A large bastite-pseudomorph after bronzite is seen on the right. The rest of the rock is of serpentine with mesh-structure, derived from olivine: it is stained in places with hydrated iron-oxide [1118].

The best-known serpentine-rocks in this country are those of the Lizard district in Cornwall[1]. The purer examples consist essentially of serpentine of various kinds, secondary iron-ore (often peroxidized), steatite, tremolite, etc., and often undestroyed relics of olivine or other original minerals of the peridotites. Professor Bonney has shewn that much of the serpentine has the character of that derived from olivine, and some of the original rocks were probably nearly pure olivine-rocks (Dun type). Others were enstatite- or bronzite-peridotites, and shew large bastite-pseudomorphs after a rhombic pyroxene (Cadgwith, Coverack, etc.; fig. 23, cf. fig. 21)[2]. Others again are altered hornblende-peridotites, some of the serpentine shewing the mesh- and some the lattice-

[1] Bonney, Q. J. G. S. (1877) xxxiii, 915–923 ; and (1883) xxxix, 21–23; Teall, 115 et seqq.
[2] See also Teall, pl. I, fig. 2 ; Cole's Micro. Stud. (1883) No. 50.

structure, while relics of olivine, hornblende, and picotite may remain (Mullion Cove, Kynance Cove, *etc.*)[1]. Augite-picrites are also represented (Menheniot, *etc.*). Here felspar has been altered into a substance resembling serpentine, which Mr Teall thinks is probably that called pseudophite. Tremolite has been formed at the expense of olivine. The augite of the original rock is often preserved. Prof. Bonney and Gen. McMahon[2], summarising the features of the Lizard serpentines, say that they "can be roughly separated into two groups : in the one a foliated mineral of the enstatite group is a conspicuous accessory ; in the other a colourless augite or hornblende, usually the latter. A few are non-porphyritic[3], and in some cases exhibit no certain traces of any pyroxenic mineral, rhombic or monoclinic, though of course a spinellid or some iron oxide is always to be detected, and in one instance (at the Rill[4], W. of Kynance Cove) the presence of a fair proportion of felspar has been asserted."

Various serpentinous rocks are found near Holyhead and in neighbouring parts of Anglesey. That of Ty-ucha is regarded by Prof. Bonney[5] as an altered olivine-rock. In rocks at Four-mile Bridge much of the serpentine has the character of that derived from augite, and the parent-rock seems to have been genetically connected with a gabbro mass. Mr Blake, however, finds indications of olivine- and enstatite-serpentine[6].

Of the numerous serpentine-rocks of Scotland[7], one at Balhamie Hill in Ayrshire has been described by Prof. Bonney[8] as an altered olivine-bronzite-rock, closely resembling that of Cadgwith in Cornwall, the structure being of the pseudo-

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[1] See Teall, pl. xv.

[2] *Q. J. G. S.* (1891) xlvii, 466.

[3] In the sense of containing no conspicuous crystals.

[4] Teall, p. 119. "The original rock, therefore, was of the nature of a picrite." See also *G. M.* 1887, 137, 138.

[5] *Q. J. G. S.* (1881) xxxvii, 45.

[6] *Rep. Brit. Ass.* for 1888, 408.

[7] For coloured plate of Portsoy serpentine see Cole's *Micro. Stud.* No. 52.

[8] *Q. J. G. S.* (1878) xxxiv, 770.

porphyritic type. Some near Belhelvie in Aberdeenshire[1] have also been enstatite-peridotites, but with the pœcilitic structure, and now shew pseudomorphs after olivine set in a framework of bastite, just as in the rock of Baste in the Harz, which has given its name to the latter mineral.

Numerous serpentine-rocks are known in the United States. Wadsworth has described peridotite-serpentines from Minnesota[2], from Plumas County, California, from Westfield and Lynnfield, Mass., and other localities[3]. Near San Francisco occur some derived from peridotites (the Potrero[4]), others from pyroxene-rocks (Angel Island[5]). The rock at Syracuse, N.Y., was shewn by Williams[6] to be an altered peridotite, sharply defined pseudomorphs after olivine and enstatite being easily detected, while the remaining constituents, *viz.* brown mica, perofskite, and chromite, are still preserved.

[1] Bonney, *G. M.* 1885, 440.
[2] *Prelim. Descr. Perid. Gabb. etc. Minn.* (1887) 29, pl. i, fig. 1.
[3] *Lithological Studies* (1884), 158–160, pl. vi, figs. 2, 5, vii, fig. 2.
[4] Palache, *Bull. Geol. Dep. Univ. Cal.* (1894) i, 165–169.
[5] Ransome, *ibid.* (1894) i, 220–222.
[6] *A. J. S.* (1887) xxxiv, 140–142. For other serpentines from New York State see Newland, *School of Mines Quarterly* (1901), xxii, 307–317, 399–410.

B. HYPABYSSAL ROCKS.

SOME petrologists are content to divide the igneous rocks into two great groups, according as their structural characters indicate consolidation under deep-seated or under superficial conditions. Others, however, recognize another group intermediate between these two. Thus Rosenbusch inserts between his 'Tiefengesteine' and 'Ergussgesteine' a group 'Ganggesteine' or 'dyke-rocks.' The rocks to be treated under the present head correspond in a general way, though not precisely, with the last named, but Brögger's name 'hypabyssal' is adopted as more accurately expressing the characters upon which the group is founded.

Although this threefold division seems to be necessitated by a comparative study of the great variety of rock-types met with in nature, it must be admitted that the hypabyssal group is a somewhat artificial one, the rocks included in it lacking any well defined set of common characteristics distinguishing them from the other two groups. Any definition would have to be framed chiefly in negative terms, and would bring together types presenting many points of difference from one another. Most of them are holocrystalline, but in some a glassy residue is found. In some families the porphyritic structure is characteristic[1], as it is in the volcanic rocks ; in others it is wanting or non-significant : but even the holocrystalline non-porphyritic types have structural and mineralogical characters, to be noted below, which differentiate them from rocks of truly deep-seated origin.

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[1] On the significance of this structure see Cross, 14th Ann. Rep. U. S. Geol. Sur. (1895) 232–235 ; Pirsson, A. J. S. (1899) vii, 271–280 ; Crosby, Amer. Geol. (1900) xxv, 299.

CHAPTER VII.

ACID INTRUSIVES.

THE acid hypabyssal rocks embrace a considerable range of varieties, bridging over the difference between the even-grained, holocrystalline granites and the porphyritic, largely glassy rhyolites. The porphyritic character is almost universal, but the ground-mass which encloses the phenocrysts may be holocrystalline, partly crystalline and partly glassy, or wholly glassy. On the nature and special structures of the ground-mass depend chiefly the several types usually recognized among these rocks. All agree in that the constituent minerals—in so far as these are developed—include in the first rank felspars rich in alkali and usually quartz, while ferro-magnesian minerals and free iron-ores occur only in relatively small quantity, and are sometimes wanting.

From an examination of their mineral constitution and characteristic structures, the more crystalline types are readily referred to their proper positions; but, in proportion as the bulk of the rock comes to consist of unindividualised glassy matter or an irresolvable cryptocrystalline 'base,' the criteria become fewer. In particular, the first stage of consolidation (that of the phenocrysts) may have been arrested before quartz (the last mineral) began to crystallize, and so, if the ground-mass consolidates as a glass, we may have a thoroughly acid rock without quartz. Thus the most glassy rocks (pitchstones) belonging to this family are not always to be distinguished by the microscope alone from less acid pitchstones. Again, they are scarcely divided from some glassy rhyolites (obsidians).

The nomenclature of the acid intrusives is confused. The name 'felsite' or—if containing evident phenocrysts of quartz—'quartz-felsite' has been applied in this country not only to these rocks but also to many volcanic rocks (acid and intermediate), and its usage lacks precision and significance. The name quartz-porphyry, borrowed from the German, covers most of the rocks, but not all, since porphyritic quartz may be wanting: this term is also used by Continental writers for the ' older ' acid lavas. For a type rich in soda, and having some mineralogical peculiarities, the name quartz-ceratophyre (Ger. Quarzkeratophyr) has been used. It will be convenient to speak of the family, as a whole, as the acid intrusives. The names applied to particular types will be noticed in connection with the ground-mass.

Constituent minerals. We notice here especially the minerals occurring as phenocrysts. Of these, the felspars include *orthoclase* (not microcline) and an acid plagioclase such as *oligoclase*. The ·two are commonly associated, and both build idiomorphic crystals with the usual types of twinning. A narrow zone of orthoclase surrounding each plagioclase crystal is seen in some rocks. The characteristic felspar of the quartz-ceratophyres is *anorthoclase*.

The *quartz* has crystallized in the ordinary hexagonal pyramids, sometimes with narrow prism-faces, but the crystals are frequently rounded and eaten into, owing to corrosion by the ground-mass, and may have lost all crystal outlines. In the rock-types most nearly approaching granites (granite-porphyries) the quartz contains fluid-pores : in other types the inclusions are mostly of glass or portions of the ground-mass (fig. 24, *A*). As already mentioned, quartz-phenocrysts are not always present.

The brown *biotite*, which occurs in many of the rocks, has the same characters as in granites, and carries the same inclusions. It is usually in good hexagonal flakes. Less commonly, in the marginal part of an intrusion, it has a blade-like habit, due to extension along the *a*-axis. The usual mode of alteration is chloritization[1]. Hexagonal flakes of *muscovite* are found in a few of the granite-porphyries only.

[1] Cohen (3), pl. LVII.

A green *hornblende* in well-built crystals is a rather exceptional constituent. The deep blue soda-bearing amphibole *riebeckite* occurs in a few rocks, always in very ragged allotriomorphic crystals (fig. 24, *B*). The *augite* of the acid
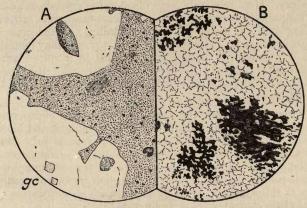
Fig. 24. × 20.

A. Quartz-porphyry, dyke, King's Cove, Arran. The quartz-phenocrysts are partly corroded, and contain inclusions of the ground-mass, as well as relatively large glass-cavities (*gc*) with the form of 'negative crystals' [3151].

B. Riebeckite-Microgranite ('paisanite'), Mynydd Mawr, Caernarvonshire. The nearly opaque crystals of sponge-like form are the dark blue soda-amphibole, riebeckite [2750].

intrusives is a pale greenish variety like that in some granites, but occurs here much more frequently. It builds good idiomorphic crystals in many granophyres and pitchstones. A few rocks rich in soda contain *ægirine*. A rhombic pyroxene (*bronzite*) is also known.

As accessories, *apatite* and *zircon* are widely but sparingly distributed, while the iron-ores are usually represented only by a little *magnetite*. Such minerals as garnet, tourmaline, and pinite pseudomorphs after *cordierite*[1] occur in special

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[1] Fouqué and Lévy, pl. xiii, fig. 5.

localities.   Some granite-porphyries carry *tourmaline* (Cornwall ; Elba).

Ground-mass and structures.   The types which approach most nearly to the plutonic habit are known as *granite-porphyry*.   Here relatively large idiomorphic crystals of quartz and felspars, with mica or some other ferro-magnesian mineral, are enclosed in a fine-textured crystalline ground-mass of felspar and quartz.   The structure of this ground may resemble that of a granite, or may be distinguished by a more marked idiomorphism of the lath-shaped felspars, usually untwinned. Mica may also occur in a second generation as part of the ground-mass.

Very common are the types in which the phenocrysts, consisting of felspars, more or less corroded quartz, and biotite or some other constituent, are embedded in a very finely crystalline ground-mass of felspar and quartz.   The elements of the ground-mass may have more or less idiomorphism. Quartz-porphyries having an evidently microcrystalline ground-mass of this kind are styled by Rosenbusch *microgranites*, the porphyritic character being understood[1].

When the texture of the ground-mass sinks to such minuteness as to be not clearly resolved under the microscope, it may be described as *cryptocrystalline* ('microfelsitic' of some authors).   For such rocks Rosenbusch uses the term felsophyre[2].   Without entering into a discussion of an obscure subject, it may be said that this cryptocrystalline ground is probably in some cases original, in other cases due to secondary change (devitrification) of a ground-mass originally glassy.

The glassy (or 'vitrophyric') type of ground-mass is seen in the rocks known as *pitchstones*.   In some of these, phenocrysts of felspar, *etc.*, are only sparingly present, the great bulk of the rock consisting essentially of isotropic glass.   This glassy ground, however, includes in many cases innumerable minute and imperfectly developed crystalline growths (*crystal-*

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[1] For chromolithograph of a microgranitic quartz-porphyry from Halle, see Berwerth, Lief. I, and of a granite-porphyry from the Odenwald Lief. IV.

[2] *Cf.* Teall, *G. M.* 1885, 108–111.

lites) with regular grouping (fig. 27). These minute bodies will be more fully noticed in connection with the acid lavas. The pitchstones frequently shew perlitic cracks, and occasionally some of the flow-phenomena which are better exhibited in lavas. Typical pitchstones, excluding lava-flows, are of quite limited distribution.

In the above types we have what may be regarded as a graduated transition from the granitic to the rhyolitic structures, the only gap, that between cryptocrystalline matter and glass, being one which the instruments at our disposal do not enable us to bridge. There is, however, a second, more or less distinct, line of transition, parallel to the former but characterized by a different set of structures, *viz.* micrographic intergrowths of felspar and quartz and regular crystalline aggregates of felspar fibres. To these structures Rosenbusch applies the somewhat inappropriate term 'granophyric,' including both micropegmatitic and microspherulitic: and the rocks having a ground-mass of this nature are very generally known as *granophyres*.

We have already noticed in some granites a micrographic intergrowth of the kind named micropegmatite; but when the whole mass of the rock, exclusive of crystals of certain minerals, takes on this character, we have a type characteristic of hypabyssal rather than abyssal rocks as here understood. In such rocks the quartz and the greater part of the felspar form a micrographic ground-mass, which may enclose idiomorphic crystals of some ferro-magnesian mineral (augite or biotite) or of felspar (mostly plagioclase). Further, the micrographic intergrowth may come in to some extent in rocks which on the whole would be placed with the granite-porphyries or the microgranitic type. When the intergrowth is on a relatively coarse scale, it is often rude and irregular, but the finer-textured '*micropegmatite*' shews great regularity and often a definite arrangement[1] (fig. 25, *A*). In particular it frequently forms a regular frame surrounding phenocrysts of felspar[2], and it can often be verified that the felspar of the

[1] Cohen (3), pl. xxxiii.
[2] For good illustrations see Irving, *Copper-bearing Rocks, L. Superior*, pl. xiv, figs. 1, 2.

intergrowth is in crystalline continuity with the felspar crystal which served as a nucleus (fig. 25, *B*). The appearance is as if the original crystal had continued to grow
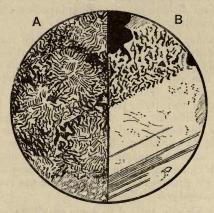
FIG. 25.   GRANOPHYRES, SHEWING MICROGRAPHIC INTERGROWTH OF
FELSPAR AND QUARTZ; × 20, CROSSED NICOLS.

A.   Crug, near Caernarvon : shewing an intricate aggregate of rather delicate micropegmatite with a tendency to irregular 'centric' arrangement [17].   *B*.   Carrock Fell, Cumberland: shewing part of a phenocryst of oligoclase with a fringe of micropegmatite.   The felspar in this is in crystalline continuity with the phenocryst; the quartz, shewn in the position of extinction, is continuous with a quartz-grain at the top of the figure [1545].

throughout the final consolidation of the rock, enclosing the residual excess of silica as intergrown quartz.   Sometimes a line of Carlsbad twinning can be traced from the crystal through the surrounding frame.   There is no doubt that plagioclase felspar, as well as orthoclase, enters into such micrographic intergrowths.   Less frequently the quartz of the intergrowth is seen to be in crystalline continuity with a quartz crystal or grain, upon which it has grown.

The finest micrographic intergrowth tends especially to a stellate or radiate ('centric') arrangement, with or without

a nucleus of an earlier crystal. As the growth becomes very delicate in texture, the sectors within which the felspar extinguishes simultaneously become narrower, and are represented between crossed nicols by dark rays when their direction makes a small angle with one of the cross-wires. When the structure is on too minute a scale to be resolved by the microscope, it may be termed, by analogy, cryptographic. The optical characters of such an aggregate appear to be determined by the minute radially arranged fibres of felspar, which obscure the quartz. The structures known as *microspherulitic* and pseudo-spherulitic in acid rocks are probably of this nature (fig. 26). Between crossed nicols they shew
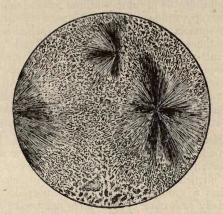
FIG. 26. GRANOPHYRE, GLAS-BHEINN BHEAG, SKYE ; × 20, CROSSED NICOLS.

The spherulites (pseudospherulites of some authors) consist of a cryptographic intergrowth of felspar and quartz arranged radially about centres. At the periphery of each spherulite the cryptographic passes into a visibly micrographic structure, and the radial arrangement becomes less marked. Between the spherulites are interspaces in which the structure is granular [2494].

characteristically a black cross, caused by extinction in those fibres which lie nearly parallel to one of the cross-wires. Such growths cluster round porphyritic crystals of quartz or felspar,

or, as innumerable closely packed minute spherules, constitute almost the whole of the ground-mass[1].

Isolated spherulites or bands of spherulites may occur in a vitreous or devitrified ground.

Leading types. We proceed to select a few examples illustrating the several points indicated above. In view of the frequent association of the different types of ground-mass in one district or even in parts of one intrusion, we shall not find it convenient to follow any strict order.

The Carboniferous 'elvan' dykes of Cornwall and Devon, as described by Mr J. A. Phillips[2] and by Mr Teall, have a microcrystalline to cryptocrystalline ground-mass enclosing large felspars, pyramidal or rounded quartz crystals, and often mica. The quartz contains either glass-inclusions[3] or fluid-pores, sometimes in the form of negative crystals[4], which may enclose a salt-cube as well as a bubble[5]. Tourmaline is of frequent occurrence in crystals or stellate groups of needles, and is sometimes seen to replace felspar. An occasional constituent is cordierite, represented by the so-called 'pinite' pseudomorphs of yellowish green micaceous flakes (Sydney Cove[6]).

The varied group of Ordovician intrusive rocks in Caernarvonshire[7] include some granite-porphyries of a well-marked type. Quartz is wanting among the phenocrysts, which are chiefly of oligoclase. One example at the head of Nant Ffrancon has a ground-mass of allotriomorphic quartz and felspar (chiefly orthoclase). The ferro-magnesian constituent

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[1] For good figures of micrographic and cryptographic structures, ranging from the micropegmatitic to the spherulitic, see Fouqué and Lévy, pl. x, fig. 2; xi, fig. 1; xii, xiv, xv, xvi. For cryptographic structure see also Cohen (3), pl. xxxiv, figs. 3, 4, and chromolith. in Berwerth, Lief. iv (from Baden, compare micrographic rock from Vosges).

[2] *Q. J. G. S.* (1875) xxxi, 334–338, pl. xvi; *cf.* Cohen (3), pl. xxii, fig. 1.

[3] Cohen (3), pl. ix, fig. 1.

[4] *Ibid.* pl. xi, fig. 4.

[5] *Ibid.* pl. xii, fig. 4.

[6] Teall, 334.

[7] *Bala Volc. Ser. Caern.* (1889) 48–56.

is biotite. Others, quarried at Yr Eifl and near Nevin, have a ground in which idiomorphic felspars are moulded by interstitial quartz. These contain augite, usually without biotite. Other rocks in the district, all augitic, shew more or less tendency to micrographic structures, and in many the whole ground-mass is of micropegmatite. Beautiful examples occur in the hills above Aber and at Moel Perfedd in Nant Ffrancon. The growth of the micropegmatite round felspar crystals is well exhibited, and in some cases a narrow zone of orthoclase is seen interposed between a plagioclase crystal and the surrounding growth. The structure is rarely so minute as to approximate to the spherulitic. Many of the smaller intrusions in the district, e.g. near Clynog-fawr, are of quartz-porphyry with a cryptocrystalline ground, which may possibly be due to devitrification. Porphyritic quartz, which is wanting in the more evidently crystalline types, appears here in corroded crystal-grains. A somewhat similar rock is that forming a low range in the neighbourhood of Llanberis. This exhibits flow-structure in places, and has been considered by Professor Bonney and others as a group of lavas.

The complex group of acid rocks near Caernarvon and eastward, which some have supposed to be of pre-Cambrian age, affords examples of granite-porphyries, micrographic rocks (fig. 25, A), microcrystalline and spherulitic quartz-porphyries, etc. The spherulitic growths often surround pyramids of quartz. The porphyritic felspars in all these rocks are mostly plagioclase, and the ferro-magnesian mineral is biotite, often green from alteration. Various granophyres and, especially, beautiful spherulitic rocks, shewing the growth round pyramidal crystals of quartz, occur at St David's[1]. The structure is of the cryptographic type, not shewing a very perfect black cross.

The Lake District contains examples of microgranites, such as the rock quarried at Threlkeld, while some minor intrusions shew a cryptocrystalline ground. Granophyres also occur, the large Buttermere and Ennerdale intrusion being of a micropegmatitic rock with either biotite or augite, resembling some Caernarvonshire examples. The dykes of Armboth and

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[1] Geikie, *Q. J. G. S.* (1883) xxxix, 315, pl. x, figs. 8, 9.

Helvellyn have a spherulitic ground-mass enclosing idiomorphic crystals of quartz and felspar. The spherulitic growth, which does not always give a good black cross, is clustered especially about the quartz crystals. A few garnets occur. These rocks are probably all Ordovician. The Devonian dykes about Shap, in Edenside, near Sedbergh, *etc.*, have microcrystalline to cryptocrystalline grounds, and some of them contain biotite rather abundantly. An intrusion near Dufton Pike[1] in Westmorland is a characteristic granite-porphyry with white and dark micas, which occur both as phenocrysts and in the ground-mass. The other phenocrysts are idiomorphic quartz and felspar, chiefly plagioclase but with a few large sanidine-crystals. A marginal modification of the rock shews a blade-like habit of the biotite, a peculiarity found also in some other rocks in Westmorland and Cumberland, such as the quartz-porphyries of Wansfell and Potter Fell and the borders of the Buttermere and Carrock Fell granophyres.

One of the most beautiful granophyres in this country is that of Carrock Fell, in Cumberland[2]. It contains a pale augite in good crystals, often uralitized or otherwise altered, and rarely a little biotite. There are also idiomorphic felspars, usually oligoclase, and some granules of iron-ore. The ground-mass shews in different specimens, or even in one slide, every gradation, from a coarse irregular micropegmatite through exquisitely regular micrographic[3] and cryptographic structures to what would be described as spherulitic. These inter-growths usually make up the whole ground-mass, though sometimes part of the quartz forms irregular grains. The arrangement is sometimes 'centric,' but more usually peripheral to the felspar phenocrysts, forming a regular border to them. It can often be seen that the felspar of the intergrowth is continuous with that of the crystal, and much of it must be plagioclase (fig. 25, *B*).

Augite- and hornblende-granophyres figure largely among the Tertiary intrusions of Scotland and Ireland, *e.g.* in Skye,

[1] *Q. J. G. S.* (1891) xlvii, 519.
[2] *Ibid.* (1895) li, 126–129.
[3] Teall, pl. xlvii, fig. 5 (misplaced 4 in key-plate).

Mull[1], and the Carlingford district. Some are quite coarse micropegmatites, or shew only a rude kind of intergrowth, and these rocks are frequently miarolitic. The more delicate micrographic and cryptographic growths are, however, represented (fig. 26). One variety, at Meall Dearg in Skye, has riebeckite instead of augite[2]. A remarkable rock from Corriegills in Arran[3] appears as if divided into polygonal areas, each enclosing a spherule with well-marked boundary and radial structure. Dr Hyland[4] has described granophyre dykes in Co. Down. These contain apparently no augite, but a little green hornblende (Newcastle) or brown mica (Hilltown).

The biotite-bearing quartz-porphyries of the Cheviots[5] have sometimes granophyric structures, but are more commonly micro- to cryptocrystalline. Frequently the ground-mass encloses patches of micropegmatite like porphyritic crystals, sometimes shewing the outlines of idiomorphic felspar. This feature is also well shewn in a microgranitic quartz-porphyry from the Black Hill in the Pentlands[6]. Among Scottish quartz-porphyries of Tertiary age those which form numerous sills and dykes in the Isle of Arran are worthy of notice. The ground-mass is microcrystalline in the larger intrusive bodies but often cryptocrystalline in the smaller (fig. 24, A).

More interesting are the well-known and beautiful Arran pitchstones[7], of which some are of acid, others of subacid composition. They form dykes, probably of Tertiary age. The phenocrysts are of sanidine, quartz, plagioclase, and augite, varying in different examples and sometimes occurring very sparingly. The ground-mass is of glass crowded with crystal-

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[1] Teall, pl. xxxiii, fig. 1.

[2] Teall, *Q. J. G. S.* (1894) l, 219.

[3] Allport, *G. M.* 1872, 541 ; Bonney, *G. M.* 1877, 506–508.

[4] *Sci. Proc. Roy. Dubl. Soc.* (1890) vi, 420–430.

[5] Teall, *G. M.* 1885, 111 ; Kynaston, *Tr. Edin. G. S.* (1899) vii, 402–408, pl. xxv, figs. 2, 3.

[6] Flett, *ibid.* 483–486, pl. xxvii, figs. 2–4.

[7] Allport, *G. M.* 1872, 1–9 ; 1881, 438 ; Bonney, *G. M.* 1877, 499–511 ; Judd, *Q. J. G. S.* (1893) xlix, 546–551, 559–561, pl. xix ; Teall, pl. xxxiv, figs. 3, 4 ; Cohen (3), pl. iv, fig. 1.

lites, which often assume peculiar groupings. In one variety needle-shaped microlites (belonites) of hornblende occur, each forming the trunk of a delicate arborescent aggregate of more minute bodies (Corriegills, fig 27, *A* and *B*). In another
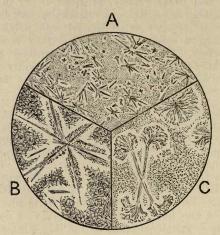
FIG. 27. PITCHSTONES, ARRAN.

A. Arborescent crystallites with stellate grouping, Corriegills ; × 20 [2752].

B. The same ; × 100.

C. Plumose crystallites with cross-like grouping ; × 100 [2751].

variety occur crosses, each of the four arms carrying a plume-like growth (Tormore, fig. 27, *C*). Again, little rod-like bodies frequently occur as a fringe arranged perpendicularly on the faces of phenocrysts. The general mass of the glass is full of very minute crystallitic bodies, but around each grouping is a clear space, indicating that the tree-like or other growth has been built up at the expense of the surrounding part. Flow-structures are only occasionally met with, and perlitic cracks are not common. Dykes of pitchstone with various crystallitic growths occur also in Skye (Glamaig, near Sligachan, and Coirechatachan near Broadford) and in Donegal (Barnesmore

Gap)[1]. All these British pitchstones are remarkable for their richness in ferro-magnesian crystallites, sometimes of hornblende, sometimes of augite.

Acid intrusives rich in soda (quartz-ceratophyres) are not yet well known in this country. Probably some of the 'soda-felsites' of Leinster[2], of Ordovician age, are to be placed here. They are microcrystalline rocks, with or without porphyritic structure, consisting essentially of predominating felspar and quartz. Plagioclase is much more abundant than orthoclase, and is sometimes albite, sometimes possibly anorthoclase or cryptoperthite.

Among American examples may be mentioned the hornblende-granite-porphyries described by Zirkel[3] for the Fortieth Parallel Survey. These carry porphyritic quartz and felspars, plagioclase being prominent, hornblende, biotite, and often sphene, with a microcrystalline ground-mass. The quartz has fluid-pores sometimes containing salt-cubes and other inclusions[4]. Typical examples occur at Franklin Buttes, Nevada, in the Oquirrh Mts, Utah, *etc.* Rocks with cryptocrystalline ground-mass ('felsite-porphyry') also occur, though in less force[5], and spherulitic varieties are found (Spruce Mt, Peoquop Range). A granite-porphyry similar to the above has been described in detail by Iddings[6] from the Eureka district, Nevada ; and Pirsson[7] has given an account of granite-porphyries, some with biotite, others with hornblende, from the Little Belt Mts, Montana. Quartz-porphyries carrying tourmaline occur in the Castle Mountain district, Montana[8], and in the Tintic Mts, Utah[9]. The quartz-porphyries of the Black Hills, S. Dakota, have been described by J. D. Irving[10]. Few typical pitchstones have been recorded in the United

[1] Sollas, *Sci. Pr. Roy. Dubl. Soc.* (1893) viii, 87–91.
[2] Hatch, *G. M.* 1889, 70–73, 545–549.
[3] *Micro. Petrogr. Fortieth Parallel* (1876), 62–67.
[4] *Ibid.* 63, 77, pl. i, fig. 5.   [5] *Ibid.* 73–80.
[6] *Monog.* xx *U. S. Geol. Sur.* (1893) 339–345.
[7] *20th Ann. Rep. U. S. Geol. Sur.* (1900) part iii, 498–511.
[8] Weed and Pirsson, *Bull.* 139 *U. S. Geol. Sur.* (1896) 99–103.
[9] Tower and Smith, 19*th Ann. Rep. U. S. Geol. Sur.* (1899) part iii, 632.
[10] *Ann. N. Y. Acad. Sci.* (1899) xii, 276–281.

States. Osann[1] notices one from the Eagle Mts in Western Texas, which recalls the Arran rocks, containing stellate groupings of green augite crystallites.

In America also a number of anorthoclase-bearing rocks have been described which fall into this family. We may note especially some of the pre-Cambrian granophyres, passing into granites (soda-granite) in the Lake Superior region and elsewhere. Such rocks have been described and figured by Irving[2] and more particularly by Bayley[3] (Pigeon Point, Minn.).

More remarkable are those rocks in which the ferro-magnesian minerals are also of soda-bearing varieties. From the Apache Mts, in Western Texas, Osann[4] has described a riebeckite-granite-porphyry (Paisani type), having scattered porphyritic felspars (microperthite) and quartz in a ground-mass containing ragged crystal-grains of riebeckite with microperthitic felspar and quartz. Washington[5] notes from Magnolia Point, Mass., a rock with a fine-textured ground-mass containing minute needles of greenish-blue glaucophane-riebeckite; and in another from Bass Rocks in the same district the coloured silicate is deep blue glaucophane[6]. Allied to the Paisani rock is that of Mynydd Mawr in Caernarvonshire[7] (fig. 24, *B*) which has ragged crystals of riebeckite with microperthitic felspars and some quartz-grains in a ground-mass of quartz and felspar with microlites of some unknown mineral. A somewhat similar rock occurs at Ailsa Craig[8], and the occurrence of riebeckite in a Skye granophyre has been mentioned above.

In other cases the ferro-magnesian is a soda-pyroxene. Brögger has described in the Christiania district an ægirine-

[1] *4th Ann. Rep. Geol. Sur. Tex.* (1892) 134.
[2] *Copper-bearing Rocks of L. Superior*, pl. xv.
[3] *Bull. No.* 109 *U. S. Geol. Sur.* (1893).
[4] *4th Ann. Rep. Geol. Sur. Tex.* (1893) 131, 132.
[5] *Journ. Geol.* (1899) vii, 111–113.
[6] *Ibid.* 117, 118.
[7] *G. M.* 1888, 225, 226; 1889, 455, 456; *Bala Volc. Ser. Caern.* (1889) 50–52.
[8] Teall, *M. M.* (1891) ix, 219–221; Heddle, *Tr. Edin. G. S.* (1897) vii, 266, pl. xv, fig. 1.

granite-porphyry in which the characteristic mineral occurs both as phenocrysts and abundantly in the ground-mass (Grorud type). Rocks more or less closely comparable with this are found in the Black Hills of Dakota[1] and at Judith Peak in Montana[2]. Varieties approximating to the same type occur near Inchnadampf in Sutherland. Mr Teall[3] describes one as consisting of polysynthetic aggregates representing original phenocrysts of alkali felspar, streaks of microcrystalline quartz (scarce), and a crypto- or microcrystalline felspathic matrix crowded with acicular microlites of ægirine. A rock of coarser texture and richer in the pyroxenic element comes from the remote islet of Rockall in the Altantic. It consists simply of ægirine, albite, and quartz[4].

[1] J. D. Irving, *Ann. N. Y. Acad. Sci.* (1899) xii, 248–257.
[2] Pirsson, 18*th. Ann. Rep. U. S. Geol. Sur.* (1898) part III, 558, 559.
[3] *G. M.* 1900, 391.
[4] Judd, *Tr. Roy. Ir. Acad.* (1897) xxxi, part III, 48–58, pl. XII.

CHAPTER VIII.

PORPHYRIES AND PORPHYRITES.

The rocks which are for convenience grouped together in this chapter belong to various hypabyssal types of intermediate chemical composition. They have not a very wide distribution, and they graduate on the one hand into the acid intrusives already discussed, on the other into the more peculiar family of the lamprophyres.

The porphyritic structure characterizes almost all the rocks in question, and in most of the types is marked by felspar phenocrysts of relatively large size. The ferro-magnesian minerals are often confined to the elements of the earlier period of crystallization. Original quartz is found in the more acid types only, and is almost always restricted to the ground-mass.

The rocks may be regarded as standing between the plutonic syenites, diorites, *etc.*, on the one hand, and the volcanic trachytes, dacites, and andesites on the other, just as the rocks treated in the preceding chapter stand between the granites and the rhyolites. According as the dominant constituent is an alkali-felspar or a soda-lime-felspar, they fall into two families, to be distinguished as porphyries and porphyrites respectively.

Under the former head we may recognize *syenite-porphyry* and *orthoclase-porphyry* (or simply porphyry), corresponding with granite-prophyry and quartz-porphyry among the acid rocks. From these orthoclase-bearing rocks have been separated others characterized by a potash-soda-felspar, under the

name *ceratophyre* (Ger. Keratophyr). There are also nepheline-syenite-porphyry and nepheline-porphyry (tinguaite, *etc.*), which are of very restricted occurrence.

Of the rocks characterized by soda-lime-felspars, the types most nearly approaching the plutonic have been styled *diorite-porphyrite*, *etc.*, the others being termed simply porphyrites. Since some ferro-magnesian mineral is usually a prominent constituent, we have the divisions *mica-porphyrite*, *hornblende-porphyrite*, and *augite-porphyrite*. If a little porphyritic quartz be present, we have a *quartz-porphyrite* (quartz-mica-porphyrite).

It must be noted that writers who make no distinction in nomenclature between intrusive and volcanic rock-types use some of the above names in a more extended sense. Thus the Continental petrologists include under the term porphyrite the 'older' andesitic lavas, while some British authors apply the same name to andesites modified by secondary changes (partial decomposition, *etc.*). Some of the altered rocks styled propylites belong to the division now to be considered, others being lavas.

Constituent minerals. The *orthoclase* phenocrysts of the porphyries are similar to those in the quartz-porphyries and other acid intrusives. In the porphyrites this mineral does not occur except in the ground-mass. A *plagioclase* felspar accompanies the porphyritic orthoclase in some of the porphyries, and forms the most conspicuous phenocrysts in the porphyrites. Here it builds idiomorphic or rather rounded crystals, with twinning often on two or three different laws. It ranges in the porphyrites from oligoclase to labradorite, and frequently shews strong zoning between crossed nicols. A parallel intergrowth of orthoclase and plagioclase is common in some porphyries. In certain types of that family also occurs a felspar which has been referred to *anorthoclase*, while it has also been explained as a minute parallel intergrowth of a potash- and a soda-lime-felspar. Viewed between crossed nicols, a crystal is often seen to be divided rather irregularly into portions with different optical behaviour, sometimes one part finely striated, another without visible striation. In certain special rocks (rhomb-porphyries) the crystal has a

peculiar habit, which gives a lozenge-shaped section; in the ceratophyres it has the usual habit, giving rectangular sections.

As phenocrysts *quartz* is found only sparingly in a few rocks, but it enters into the ground-mass of all the more acid of the porphyries and porphyrites, though less abundantly than in the true acid rocks.

The most usual ferro-magnesian minerals are brown *biotite* and a pale or colourless idiomorphic *augite*. Some of the porphyrites have *hornblende* in sharply idiomorphic prisms, often twinned: it is more usually brown than green. In rocks rich in alkali the coloured constituent is often ægirine-augite or true *ægirine*.

As accessories, *apatite* and *iron-ores* (often titaniferous) may occur in varying quantity, the latter not being abundant. Exceptionally *olivine* and other minerals are present.

In the few rocks which contain *nepheline* that mineral occurs in one or two generations. As phenocrysts it is idiomorphic, while the little crystals in the ground-mass may or may not have definite shape. The 'liebenerite' pseudomorphs in certain porphyries have been supposed to represent nepheline. They consist essentially of a pale mica, and may with equal probability come from the destruction of cordierite. Some of these rocks rich in alkali carry melanite *garnet*.

Ground-mass and Structures. In the great majority of the rocks here considered the ground-mass is holocrystalline, with a fine texture and with various types of structure. It consists essentially of felspar or, in the more acid members, of felspar and quartz. In the porphyries the felspar is usually in minute prisms, short in comparison with their length, and as a rule untwinned. Quartz, if present, occurs interstitially. The little prisms may have more or less of a parallel arrangement, due to flow. Such short and relatively stout prisms are usually referred to orthoclase: if the crystals have the 'lath'-shape, they are probably of a plagioclastic variety. Any approach to an allotriomorphic character is uncommon, and the micrographic intergrowths so

frequent among the acid intrusives are not found here. In the nepheline-bearing rocks a more allotriomorphic type of structure is often found; while the bostonites and allied rocks shew an approach to the volcanic trachytes, often with marked flow-structure.

The ground-mass of the porphyrites is also in general holocrystalline, consisting essentially of felspar, or, in the more acid varieties, of felspar and quartz. In this latter case the rocks may reproduce some of the characteristic structures noted in the preceding chapter, such as the cryptocrystalline and the micrographic. Other porphyrites have the 'orthophyric' type of ground-mass (with short felspar-prisms), as in the porphyries, but there is every gradation from this to the allotriomorphic. In some of the more basic members the ground-mass consists of little lath-shaped plagioclase prisms with more or less noticeable flow-arrangement, an approach to the character of some andesites ('pilotaxitic' structure).

Glassy and vitrophyric rocks are not unknown in the families in question. Some of the Arran pitchstones, for example, have the composition of intermediate rather than acid rocks.

Leading types. Only a few illustrative examples will be selected, chiefly from British and American rocks.

As an example of *syenite-porphyry* may be noticed the rock quarried at Enderby in Leicestershire. It contains phenocrysts of a strongly zoned plagioclase felspar and of pale greenish brown hornblende with, more sparingly, flakes of biotite and round grains of quartz in a moderately fine-textured groundmass of quartz and felspar, apparently orthoclase.

Syenite-porphyries in considerable variety have been described from the United States. Some with hornblende occur in the Little Belt Mts, Mont.[1] From Cape Ann, Mass., Washington[2] describes dykes of quartz-syenite-porphyry, in which the coloured silicates are green hornblende and subordinate biotite. This rock he compares with Brögger's

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[1] Pirsson, 20*th Ann. Rep. U. S. Geol. Sur.* (1900) part III, 513–515.
[2] *Journ. Geol.* (1899) vii, 108, 109.

Lindö type, from the Christiania district, which, however, is typically non-porphyritic. A rock from Coney Island, Salem, Mass., has abundant phenocrysts of felspar (microperthite and cryptoperthite) in a ground-mass of similar felspars and needles of a greenish blue soda-amphibole (catophorite), with fluxion-structure. Augite-syenite-porphyry has been noted at Lake Chatauqua, N.Y., Albany, N.H. (with accessory bronzite), and other places.

Richer in alkali is the ægirine-syenite-porphyry (Sölvsberg type) described by Brögger in the Christiania district. Here the structure of the ground-mass approaches that seen in the trachytic lavas and in the bostonites noticed below. A similar rock is that described (under the name 'acmite-trachyte') by Wolff and Tarr[1] from the Crazy Mts in Montana. The pheno-crysts are of anorthoclase and augite (bordered by ægirine) with occasional sodalite, and the ground-mass is of lath-shaped felspars (chiefly anorthoclase) and needles of ægirine, with a variable amount of nepheline and secondary analcime. Rocks more or less comparable with this occur near Manchester in Massachussetts[2] and in the Apache Mts of Texas. From the Sierra Nevada of California Turner[3] has described a 'soda-syenite-porphyry' resembling in some respects the Sölvsberg type; and a glaucophane-bearing rock of somewhat similar characters is found at Cape Ann, Mass.[4] These rocks have not, however, the trachytic structure, and further differ in the nature of their ferro-magnesian component.

The most usual type of *orthoclase-porphyry* (orthophyre of Rosenbusch) is exemplified by dykes and sills in the Carboni-ferous of Thuringia, in the Vosges, and in other districts. Besides the orthoclase phenocrysts there may be some of plagioclase. The ferro-magnesian minerals are only sparingly represented, and may be biotite, hornblende, or augite. The ground-mass is holocrystalline with the structure styled ortho-

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[1] *Bull. Mus. Comp. Zool. Harv.* (1893) xvi, 227–230.
[2] Eakle, *A. J. S.* (1898) vi, 489–492; Washington, *Journ. Geol.* (1899) vii, 119, 120.
[3] *17th Ann. Rep. U. S. Geol. Sur.* (1896) 665, 666, pl. XLIII.
[4] Washington, *A. J. S.* (1898) vi, 176–179. See also *Journ. Geol.* (1899) vii, 114–119.

phyric, in which short prisms of untwinned felspar are associated with some interstitial quartz.

Of a different type are the rocks forming North Berwick Law and the Bass Rock. They have been described[1] under the name trachyte, with the associated lavas which they closely resemble (see Chap. XII.), but may be mentioned in this place. The felspar of which they are almost wholly composed is rich in soda as well as potash, and the non-porphyritic, trachytoid structure of the rocks allies them with the bostonites. An albite-porphyry has been recorded from Ben Brachaid in Sutherland, containing albite phenocrysts in a ground-mass essentially of the same mineral[2].

The typical *bostonites* occur at Marblehead Neck near Boston, Mass.[3], in the Adirondacks[4], near Montreal, at Livermore Falls and Shackford, N.H., in the Apache Mts, Tex., *etc.*, as dykes in connection with nepheline-syenite or other plutonic rocks, and especially in intimate association with dykes of lamprophyre (camptonite). The bostonites consist essentially of felspar, quartz being never abundant and the ferro-magnesian silicates typically absent. Phenocrysts may or may not be developed, the bulk of the rock being a ground-mass of little felspar rods, often with partial flow-disposition and recalling the structure of the trachytes (fig. 28, *A*). In many examples a high percentage of soda, with little or no plagioclase evident, points to a soda-orthoclase or anortho-clase, and indicates an affinity with the ceratophyres. Rocks approaching bostonite in character occur in the Limerick district[5] and in the western part of Sutherland; and an allied rock is described by Dr Flett[6] as forming a dyke at Onston Ness in the Orkneys. This rock carries felspar phenocrysts:

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[1] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 123, 124, pl. I, figs. 3, 4.

[2] Heddle, *M. M.* (1884) v, 141.

[3] Wadsworth, *Proc. Bost. Soc. Nat. Hist.* (1881) xxi, 290; Sears, *Bull. Mus. Comp. Zool.* (1890) xvi, 169–171; Washington, *Journ. Geol.* (1899) vii, 293.

[4] Kemp and Marsters, *Trans. N. Y. Acad. Sci.* (1891) xi, 14–16 ; *Bull. No.* 107 *U. S. Geol. Sur.* (1893) 18–22.

[5] Watts, *Guide*, 93.

[6] *Tr. Roy. Soc. Edin.* (1900) xxxix, 872, 873, pl. I, figs. 1, 2.

the ground-mass has the trachytic structure towards the margins of the dykes, but is allotriomorphic in the central part.
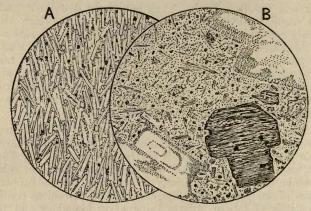
FIG. 28.   × 20.

A. Bostonite, Marblehead Neck, Massachussetts; consisting essentially of little crystals of felspar (anorthoclase) with fluxional arrangement [2464].

B. Mica-porphyrite, Colven, near Dalbeattie, Kirkcudbrightshire; with phenocrysts of zoned plagioclase and decaying biotite [2594].

Among the Devonian intrusions of the Christiania district occur the singular rocks known as *rhomb-porphyry* (Ger. Rhombenporphyr), and they may be studied in numerous boulders in Holderness and the Eastern Counties. The phenocrysts of potash-soda-felspar, with their unusual crystallographic development, have been alluded to above. The crystals are often rounded and corroded, and they contain numerous inclusions of materials like the ground-mass. Some of the rocks contain pseudomorphs after olivine. The fine-textured holocrystalline ground-mass consists of short prisms of felspar (probably orthoclase) with little granules of augite. Apatite is often plentiful, and grains of titaniferous iron-ore occur. Rhomb-porphyries have been discovered by Osann in the Apache Mts, Tex.

The name *ceratophyre* was first used by von Gümbel for a rather varied group of rocks in the Fichtelgebirge. Somewhat similar rocks have been described from Saxony, Westphalia, the Harz, and other areas. Porphyritic quartz does not occur in the ceratophyres proper, and felspar is the predominant mineral in both phenocrysts and ground-mass. The phenocrysts have the peculiarities attributed to anorthoclase or to a cryptoperthite intergrowth. The commonest ferro-magnesian element is a pale augite (diopside). The felspar prisms of the ground-mass may be short and unstriated or lath-shaped and striated, and the more acid members have a little interstitial quartz.

Rosenbusch has given the name *tinguaite* to certain 'dyke-rocks' which have the composition of the (plutonic) nepheline-syenites and the (volcanic) phonolites, with structural characters which place them between those two families. Such rocks are associated with nepheline-syenites in the Serra do Tingua and other places in Brazil, and in Massachussetts (Essex County), Arkansas[1] (Fourche Mt), and Texas (Apache Mts). Phenocrysts of orthoclase, often with marked tabular habit and with the characters of sanidine, are embedded in a fine-textured holocrystalline ground-mass of orthoclase with nepheline, ægirine, *etc.* This ground is typically allotriomorphic: when the little felspars take on the lath-shape with fluxional arrangement, the rocks do not differ essentially from phonolites. There may be phenocrysts of nepheline, and in one type (leucite-tinguaite) large pseudomorphs of orthoclase and elæolite occur in the form of leucite. This latter type has been described from Brazil[2], Arkansas[3] (Magnet Cove), and Montana[4]. From the last-named state comes also a variety intermediate between the true tinguaite and the Sölvsberg type mentioned above (Landusky in the Little Rocky Mountains[5]). A more basic nepheline-bearing type,

[1] J. F. Williams, *Igneous Rocks of Arkansas*, vol. ii of *Ann. Rep. Geol. Sur. Ark. for* 1890, 100–106.
[2] Derby, *Q. J. G. S.* (1891) xlvii, 251–265.
[3] J. F. Williams, *l.c.* 277–286.
[4] Pirsson, *A. J. S.* (1895) l, 394–398.
[5] Weed and Pirsson, *Journ. of Geol.* (1896) iv, 419–421.

on the other hand, occurs at Magnet Cove, Ark.[1], and at Beemerville, N.J.[2], having phenocrysts of nepheline up to an inch in diameter in a tinguaitic ground-mass composed chiefly of nepheline, charged with ægirine-needles, with some ortho-clase, *etc.* A tinguaitic rock at Pickard's Point, Mass.[3], contains analcime and nepheline as the main elements of its ground-mass, and this analcime is considered to be a primary mineral[4]. Here may be mentioned also a remarkable dyke-rock (Heron Bay type) from the Lake Superior region, consisting to the extent of about one-half of analcime, in which are embedded orthoclase, labradorite, and ægirine[5].

Coming now to rocks of dioritic affinities, we may mention a quartz-*diorite-porphyrite*, from Sweet Grass Hills, Montana[6], and a quartz-mica-diorite-porphyrite, approaching granite-porphyry, from Electric Peak in the Yellowstone Park[7]. This has abundant small phenocrysts of felspars, quartz, and biotite, with a little hornblende, and a granular ground-mass of felspar and quartz. In the same district occur porphyrites, generally *hornblende-porphyrites*[8], carrying abundant phenocrysts of lime-soda-felspar and hornblende, with usually biotite and oc-casionally uralitized augite, in a fine-grained ground-mass. When the latter is rich in quartz, this mineral tends to form micropœcilitic patches enclosing the little felspar-prisms ; when quartz is scarce, the felspars, which are, at least in the main, plagioclase, tend to have a felted arrangement. The ground-mass also contains some hornblende and biotite. Resembling the Electric Peak rocks, and like them of somewhat acid character as a whole, are the hornblende-porphyrites and hornblende-mica-porphyrites described by Cross[9] from the

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[1] J. F. Williams, *l.c.* 259–261.
[2] Kemp, *Trans. N. Y. Acad. Sci.* (1892) xi, 66, 67. This type is the 'sussexite' of Brögger, constituting the most basic member of a 'rock-series' of which the other members are grorudite, sölvsbergite, and tinguaite.
[3] Sears, *Bull. Essex Inst.* (1893) xxv.
[4] Washington, *A. J. S.* (1898) vi, 182–186.
[5] Coleman, *Rep. Bur. Mines Toronto* (1899) viii, part 2, 172, 173.
[6] Weed and Pirsson, *A. J. S.* (1895) l, 311.
[7] Iddings, 12*th Ann. Rep. U. S. Geol. Sur.* (1892) 617, 618.
[8] *Ibid.* 588–594.
[9] Cross, 14*th Ann. Rep. U. S. Geol. Sur.* (1891).

laccolites and associated intrusions of the Henry and Abajo Mts in Utah, the West Elk and El Late Mts in Colorado, *etc.* Among the phenocrysts the dominant minerals after plagioclase felspar (oligoclase or andesine) are hornblende and to a less extent biotite, while augite and hypersthene occur only locally. Quartz is also developed porphyritically and in certain cases large crystals of orthoclase, which, however, seem to belong rather to the same stage of consolidation as the ground-mass (Mt Carbon and Gothic Mt, in the West Elk group, *etc.*). The ground-mass is essentially an aggregate of orthoclase and quartz. Rocks generally resembling the above are described by Pirsson[1] from the Judith Mts in Montana. There are transitional varieties between diorite-porphyrite and syenite-porphyry or quartz-syenite-porphyry.

Various rocks of the porphyrite family are known in the British Isles, and especially in Scotland. Numerous *mica-porphyrite* dykes, of Old Red Sandstone age, occur in the Cheviots[2]. The felspar phenocrysts (oligoclase-andesine) are frequently rounded, and shew carlsbad and albite twinning. The biotite-flakes are often bent, and sometimes shew a resorption border. A colourless augite may also occur, and magnetite and apatite are minor constituents. The ground-mass is microcrystalline, fine-textured, and often obscured by decomposition. Quartz plays a variable part in it, and there are some transitions to granophyre and quartz-porphyry. Indeed the mica-porphyrites in general often carry a notable amount of quartz in their ground-mass. The handsome rock which forms large intrusive sills in the Torridon Sandstone of Cansip, Sutherland, may also be placed here. It has large, frequently broken, phenocrysts of albite-oligoclase, and ortho-clase also occurs, sometimes intergrown with the plagioclase. The dominant coloured mineral is biotite, but Mr Teall also notes augite, either colourless or green or the former bordered by the latter. Calcite pseudomorphs in the form of augite are common. These minerals, with some magnetite, are set in a fine microcrystalline ground-mass of felspar and quartz.

[1] 18*th Ann. Rep. U. S. Geol. Sur.* (1898) part III, 562–564.
[2] Watts, *Mem. Geol. Sur. Eng. and Wales, Expl. Sh.* 110 *S.W.* (1895) 62, 63 ; Kynaston, *Tr. Edin. G. S.* (1899) vii, 398–402.

The dykes described by Mr Teall[1] in Kirkcudbrightshire are mostly mica-hornblende-porphyrites. The phenocrysts are of zoned plagioclase in large individuals, green hornblende and brown biotite, both in good crystals, and sometimes corroded grains of quartz, while the fine-textured ground-mass contains quartz and orthoclase in addition to the other minerals named. In some varietes the hornblende is almost or quite wanting (fig. 28, B).

Of hornblende-porphyrites we may recognize more than one variety. Some of the Scottish examples are of tonalitic rather than dioritic affinities (Cowal district of Argyllshire[2]). Again, there are the rocks which form sills of Lower Palæozoic age in the Assynt district of Sutherland (Inchnadampf, etc.[3]). Here the hornblende is green and in very perfect crystals, often twinned : they sometimes shew zonary colouring, and are occasionally hollow. A colourless augite in imperfect crystals sometimes accompanies the hornblende. The plagioclase phenocrysts shew strong zonary banding between crossed nicols. Magnetite and apatite are present sparingly. The microcrystalline ground-mass is of felspar with subordinate quartz. These rocks are part of a variable set of intrusions. On the one hand is a non-porphyritic and coarser-textured type with allotriomorphic felspar (diorite), on the other a type with more abundant hornblende in two generations and with a panidiomorphic ground-mass (camptonite, see Chap. X. and fig. 33).

A hornblende-porphyrite of basic composition is seen in the Mawddach valley, near Dolgelly. It contains large and rather irregularly bounded twin-crystals of brown hornblende in a much decomposed matrix. Mr Phillips[4] termed this hornblende uralite, but there is no clear evidence that it is other than an original mineral.

The rocks to which the name augite-porphyrite has been applied by German petrologists seem to be for the most part

[1] Mem. Geol. Sur. Scot., Expl. Sh. 5 (1896), 44, 45, and Silur. Rocks Scot. (1899) 626, 627.

[2] Teall, Mem. Geol. Sur. Scot., Geol. of Cowal (1897), 103.

[3] Teall, G. M. 1886, 346–350.

[4] Q. J. G. S. (1877) xxxiii, 427–429, pl. xix.

old augitic lavas, though intrusive types are also included. Such rocks, probably of Triassic age, are represented in the Monzoni district in the southern Tirol. Augite is, however, a frequent accessory mineral in the hornblende-porphyrites, and in particular occurrences may become the dominant coloured element of the rock. Thus in the Henry Mts Cross remarks augite-porphyrites at Mount Pennell and Mount Hillers; but these are mainly from sheets, while the great laccolites themselves are of the hornblendic type.

CHAPTER IX.

DIABASES.

The larger intrusive bodies of hypabyssal pyroxenic rocks, whether intermediate or basic in composition, have petrographical features which characterize them as a group with considerable individuality. It is to these rocks that we shall apply the name diabase. Like their plutonic equivalents, the gabbros, they are holocrystalline and typically non-porphyritic; but they differ from the normal gabbros in their less coarse texture, in the absence of diallagic and other 'schiller' structures, and in the mutual relations of the felspar and augite which are their two chief constituents. In these respects there are, however, transitions between the two sets of rocks.

The diabases occur as large dykes, sills, and laccolitic or other masses. Smaller intrusions of rocks having a similar chemical composition commonly have more of the petrographical characters of volcanic rocks. For these we shall retain the names dolerite, andesite, basalt, *etc.*, and they will be excluded from this place.

The name diabase has been, and still is, employed in different senses. By the German school it is restricted to the older rocks, whether hypabyssal or volcanic, dolerite and basalt being terms reserved for rocks of Tertiary or later age. Mr Allport shewed very conclusively that such a distinction corresponds with no real difference between the older and the newer rocks, and he abandoned the name diabase in favour

of dolerite for all. The rocks so designated by Allport include some of the hypabyssal and others of the volcanic type. English writers have followed him in admitting no criterion of geological age into their classification and nomenclature, but some of them have inconveniently employed the name diabase for a more or less decomposed dolerite.

According to the absence or presence of the basic silicate olivine, the rocks of the present family are often divided into *diabases proper* and *olivine-diabases.* Olivine is in general found in the more basic members of the family, but this division does not correspond very exactly with the chemical division into intermediate (or sub-basic) and basic. By the presence of some other special mineral we may distinguish such types as *quartz-diabase, bronzite-diabase*, and *hornblende-diabase;* or again quartz-bronzite-diabase and olivine-hornblende-diabase.

Various other names have been used for particular types of diabasic rocks. Among the hornblende-bearing diabases of the Fichtelgebirge von Gümbel distinguished two types; proterobase, containing original hornblende in addition to augite, and epidiorite, in which the hornblende is all derived from augite. Some writers have extended these names to cover all diabasic rocks characterized by primary and secondary hornblende respectively[1]. The old field-term 'greenstone,' referring to the staining of the rocks by chloritic and other decomposition-products, included not only diabases but diorites, picrites, altered dolerites, *etc.*, and so had no precise signification.

Constituent Minerals. The *felspars* of the diabases range from oligoclase to anorthite in different examples : varieties of labradorite are perhaps the most common. The crystals have a strong tendency to idiomorphism, with columnar or sometimes tabular habit. Twin-lamellation on the albite law is universal, and is often combined with carlsbad twinning, but the pericline law is not so common. Zonary growth is not often shewn, except when a later set of

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[1] It is probable, however, that secondary hornblende has often been mistaken for primary.

felspars occurs, of shapeless outline and more acid composition ; these shew strong zoning between crossed nicols. Inclusions are not common, except glass-cavities and needles of apatite. Decomposition gives rise to calcite-dust, to finely divided material, which may be mica, to zeolites, or to granular epidote. The crystals also become charged with strings and patches of green chloritic substances, probably derived in part from the pyroxene.

The common pyroxenic constituent is an *augite*, usually without crystal outlines. It varies in thin slices from brown to nearly colourless, and rarely shews sensible pleochroism. Zonary and 'hour-glass' structures are sometimes seen. The orthopinacoidal twin is common, and in some cases there is a fine basal lamination[1] in addition (Whin Sill). The commonest decomposition-products are pale green, fibrous or scaly aggregates of serpentinous and chloritic substances. The former may be recognized by their low refractive index and moderately high birefringence ; the latter are usually very feebly birefringent or sensibly isotropic, and shew distinct pleochroism. Another change to which augite is subject is that which results in a light-green 'uralitic' hornblende. This is usually, but not always, fibrous in structure.

Some diabases contain *bronzite* in addition to augite. It is in more or less idiomorphic crystals, with faint pleochroism, and gives rise by alteration to pseudomorphs of light green fibrous bastite. Only occasionally does *hornblende* appear as an original constituent. It seems to be characteristically a brown variety. Brown *biotite* is also a rare accessory.

A little *quartz* is found in some of the less basic diabases, occurring interstitially. Whether it is original or a decomposition-product is sometimes difficult to decide, but when the mineral forms part of a micrographic intergrowth with felspar its primary nature may safely be assumed.

The *olivine*, which occurs in very many diabases, builds more or less rounded idiomorphic crystals or grains, sensibly colourless or very pale. It has the same mode of alteration as in the olivine-gabbros and peridotites.

[1] Teall, *Q. J. G. S.* (1884) xl, pl. xxix, fig. 1.

The iron-ores, which, in contrast with some gabbros, the diabases contain abundantly, include *ilmenite* and *magnetite*. The two are very commonly associated, and some so-called titaniferous magnetite has been supposed to be a minute intergrowth of the two[1]. They are easily distinguished when they occur as crystals or skeleton-crystals. In most cases the ilmenite has given rise to more or less of its characteristic
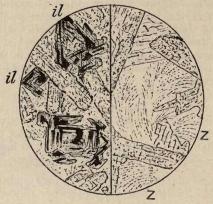
FIG. 29. DECOMPOSING DIABASE, DENEIO, NEAR PWLLHELI, CAERNARVONSHIRE ; × 20.

This shews decomposing felspar-crystals and ophitic augite, with ilmenite-skeletons (*il*), crusted with leucoxene, and patches of radiating fibres of a zeolitic mineral (*z*) [123].

decomposition-product, grey cloudy masses of semiopaque leucoxene[2] (fig. 29).

Long columnar or needle-like crystals of *apatite* occur in most diabases, but in some are capriciously distributed.

Structure. As regards structure, the diabases offer a contrast to normal plutonic rocks, owing mainly to the fact that the crystallization of the felspar has preceded that of the

[1] Teall, *Q. J. G. S.* (1884) xl, 650, 651, pl. xxix, figs. 4–7.
[2] Cohen (3), pl. lxi, fig. 4 ; Teall, pl. xvii, fig. 2.

dominant ferro-magnesian constituent. As seen in a slice, the columnar crystals of felspar shew more or less elongated sections, with no law of arrangement, and around or between these the augite is moulded. The last-named mineral in most cases distinctly wraps round the felspar crystals, and often forms plates of some extent, enclosing many of them. This is known as the *ophitic* structure[1] (fig. 30). In other cases the augite tends to form more or less rounded grains embedded in a plexus of lath-shaped felspars, adjacent grains not being parts of one crystal but shewing different orientations. This is what Prof. Judd[2] has styled the *granulitic* structure : he considers it due to movement towards the end of the process of consolidation. In both types, if olivine is present it is always idiomorphic towards the augite, but may be penetrated by the felspar prisms. The rhombic pyroxene, too, is constantly of earlier crystallization than the augite, and may shew good outlines. The iron-ores are often idiomorphic, but magnetite may be in part later than the felspar. When, as is sometimes the case, a subordinate felspar, of later consolidation than the dominant kind, is present, it has crystallized with or after the augite, and is always shapeless.

The typical diabases thus present a very uniform structural character, which in its best development is almost peculiar to them. In a few diabases, however, the augite, especially if not abundant, is partially idiomorphic, and the same is true of rocks which are on the border-line between diabase and gabbro. A porphyritic character, due to the development of relatively large crystals of felspar at an early stage, is not common : it is sometimes connected with an increasing fineness of texture of the rock on approaching the edge of an intrusive mass. Other occasional marginal peculiarities are flow-phenomena, vesicles or amygdules, and the development of a glassy base or sometimes of variolitic and allied structures. Rocks having these features and occurring as marginal modifications of normal diabases do not differ in any essential from certain types of lavas, and will therefore not be noticed in this place.

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[1] See chromolithograph of diabase in Berwerth, Lief. 1.
[2] *Q. J. G. S.* (1886) xlii, pp. 68, 76, and figs. pl. v.

Leading types. A true *quartz-diabase* is not often met with. In any but quite fresh rocks, at least, it is not possible to be certain that quartz occurring interstitially is really an original constituent of igneous origin. Among the numerous dykes traversing the old gneiss of Sutherland are diabases of which some are quartz-bearing (Loch Glencoul, *etc.*). The chief constituent minerals are a basic plagioclase and a pale or colourless augite, the relations between the two being rather variable. A green or yellow-green hornblende occurs as a marginal alteration of the augite, especially around the grains of magnetite, and a little brown biotite is also associated with the latter. The hornblende is connected with mechanical stress in the rock, and specimens may be collected to shew the complete amphibolization of the augite.

A well-known rock in the north of England is the Great Whin Sill[1], which is intrusive in Lower Carboniferous strata, and extends from the Northumberland coast to the Eden valley. In its coarser central parts it sometimes approaches a gabbro in aspect, the augite becoming idiomorphic; the fine-textured portions near the margin, on the other hand, take on an andesitic character, developing perhaps some glassy base; but the bulk of the intrusion is of diabase of a distinctive type. The normal structure is more or less ophitic, and the dominant constituents are a lath-shaped felspar, near andesine, and a pale brown augite, often with basal striation. The iron-ore is titaniferous, and may perhaps represent minute intergrowths of magnetite and ilmenite. An accessory mineral is bronzite, tending to be replaced in the usual fashion; brown mica is occasionally seen, and a little brown hornblende is often present, bordering the augite with crystallographic relation. Quartz is detected in all the coarser varieties of the rock, and is at least in part original, since it frequently occurs in micrographic intergrowth with felspar. The rock is thus a quartz-diabase. Mr Teall[2] has described a similar rock from Ratho, near Edinburgh. With these rocks we may also compare that near Stirling[3]. The general mass of this is a simple diabase, the augite often shewing basal striation, but there

[1] Teall, *Q. J. G. S.* (1884) xl, 640–657, pl. xxix: also *Brit. Petr.* pl. xiii. fig. 2.
[2] Teall, p. 190.   [3] Monckton, *Q. J. G. S.* (1895) li, 480–491.

are coarse-textured veins, which contain quartz in delicate micrographic intergrowth with part of the felspar.

The Penmaenmawr[1] intrusion, probably of Ordovician age, is also characterized by quartz occurring interstitially in a micrographic intergrowth. In this rock bronzite becomes an essential constituent, being quite as abundant as the pale brown augite. The latter mineral often shews the delicate basal striation already noticed. Biotite is sometimes rather abundant, but the dominant type of rock is a *quartz-bronzite-diabase*. The structure of the rock is rather granulitic than ophitic, and it usually shews some approach to the characters of volcanic rocks in the occurrence of more than one generation of felspar. Some of the latest shapeless crystals are to be referred to orthoclase. The rock passes into a type which would be properly described as an andesite. The general body of the rock is traversed by comparatively coarse segregation-veins of more acid composition[2].

Quartz-diabases are not unknown in America; *e.g.*, at Newhaven[3] and Medford, Conn., in the Province of Quebec, and near St John, N.B.[4]

The numerous sills of Ordovician age in Caernarvonshire[5] are of *diabase without olivine*, and have almost universally the ophitic structure. The felspar gives lath-shaped or rectangular sections from ·05 to ·5 inch long, with albite- but only occasionally pericline-lamellation: it often gives extinction-angles indicating labradorite and neighbouring varieties. The augite is pale brown to almost colourless, and very rarely shews any approach to idiomorphism. Besides the commoner decomposition-products, there is often a fibrous colourless hornblende, fringing the augite but occupying the place of destroyed felspar, *etc.* The iron ores include both magnetite and ilmenite, often together, and apatite is locally plentiful. Rhombic pyroxene is wanting, as well as olivine, while original hornblende and

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[1] *Bala Volc. Ser. Caern.* (1889) 65 ; Teall, pl. xxxv, fig. 2.
[2] Waller, *Midland Naturalist* (1885), viii, 1–7.
[3] Pirsson, in Diller, 264–273.
[4] Matthew, *Trans. N. Y. Acad. Sci.* (1895) xiv, 213, 214, pl. xv, fig. 2.
[5] *Bala Volc. Ser. Caern.* (1889) 75–86,

quartz are practically absent, and biotite very exceptional. These Caernarvonshire diabases are thus of very simple mineralogical constitution. Despite the absence of olivine, they are of thoroughly basic composition. The diabases of similar age in Wicklow are also free from olivine, and are probably of more acid composition, some of them containing quartz. They are characterized by a partial or even total conversion of the ophitic augite into hornblende, with other changes ascribed to dynamic metamorphism[1].

A different type is presented by the post-Carboniferous (probably Tertiary) dykes found in the northern half of England and in North Wales, *e.g.* on the Menai Straits. The smaller ones are augite-andesites; the larger may be classed as dolerites or as diabases shewing a tendency to a doleritic type. The dominant felspars give the usual rectangular section, and the light brown augite moulds round them in ophitic fashion; but a special feature of the rocks is the occurrence of a second and subordinate generation of felspar in allotriomorphic crystal-grains which have consolidated, on the whole, about simultaneously with the augite. They have less close twin-lamellation than the dominant felspars, are of more acid composition, and always shew a marked zonary banding between crossed nicols. These rocks contain magnetite, but not ilmenite. Very similar dykes, of Tertiary age, are abundant in some parts of Scotland and the Inner Hebrides.

Numerous *olivine-diabases* are associated with the Carboniferous strata of the Midlands. Good examples are seen in the Clee Hills, Shropshire[2]. The rock of Pouk Hill[3], near Walsall, is an ophitic olivine-diabase. In that of Rowley, near Birmingham, the augite occurs in little grains and tends to be idiomorphic[4], or again there is a micrographic intergrowth of augite and felspar[5]. In this rock are relatively acid

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[1] Hatch, *G. M.* (1889) 263–265.
[2] This and many other British examples were noticed by Allport, *Q. J. G. S.* (1874) xxx, 529–567.
[3] Watts, *Pr. Geol. Ass.* (1898) xv, 397–400.
[4] Teall, pl. XI.
[5] *Ibid.* pl. XXIII, fig. 2,

segregation-veins, in which part of the felspar is orthoclase[1].
A few of the Derbyshire 'toad-stones' have the structure of
ophitic diabases[2] (fig. 30), and in some of them Mr Arnold-
Bemrose[3] has described certain peculiar pseudomorphs after
olivine.
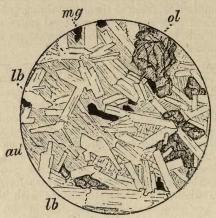
FIG. 30.   OLIVINE-DIABASE, BONSALL, DERBYSHIRE ;   × 20.

Shewing olivine-grains (ol), more or less completely serpentinized,
magnetite (mg), and lath-shaped crystals of labradorite (lb), set in a
framework of crystalline augite (au), which wraps round and encloses
the felspar with typical ophitic structure [424].

Numerous intrusions of olivine-diabase, some of Carbon-
iferous and others of Tertiary age, occur in the southern half
of Scotland[4] and in the western islands.   As distinguished
from the basalts and dolerites, they are typically ophitic rocks
consisting of magnetite, olivine (often in fresh crystals), lath-
shaped felspar, and crystal-plates of augite.   Zeolites are

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[1] Waller, *Midl. Natst.* (1885) viii, 261–266.
[2] Teall, pl. IX ; Arnold-Bemrose, *Q. J. G. S.* (1899) lv, pl. xx, figs.
1–3.
[3] *Q. J. G. S.* (1895) li, 613–616, pl. xxiv.
[4] The rock quarried at Corstorphine near Edinburgh is a good example
of the earlier set : see coloured plate in Cole's *Stud. in Micro. Sci.* (1882)
No. 32.   For Tertiary examples see Teall, pl. x.

frequent among the secondary products. Sills, dykes and rocks of ophitic olivine-diabase are abundant also in the Tertiary volcanic plateau of Antrim[1].

Without entering into an account of particular occurrences in America, it may be stated that dykes of diabase, and especially of olivine-diabase, are widely distributed in the Archæan and other ancient formations of Canada and the northern United States[2].

Of *hornblende-bearing diabases* a good example is found in a large dyke which runs on the east side of Holyhead Mountain[3]. The brown hornblende is very frequently in parallel intergrowth with augite, which it tends to envelope. The augite is a pale malacolite variety. Apatite and magnetite are abundant. The structure of this rock is very variable, sometimes the felspar, sometimes the augite, presenting idiomorphic boundaries to the other. Other examples occur in the neighbourhood of Penarfynydd, near Sarn, in the southwest of Caernarvonshire. Of diabases containing derivative hornblende we have numerous examples in this country. Many of the ' greenstones ' of Cornwall are much altered diabases shewing uralitization, chloritization, and other changes ; but the rocks so named in the field include also old basic lavas and other types[4].

We may briefly notice in this place the peculiar group of rocks named *teschenite* by Hohenegger, occurring as intrusions in the Cretaceous of Silesia and Moravia (Teschen, Neutitschein, Söhla, *etc.*). They consist mainly of augite, brown hornblende, plagioclase, apatite, and analcime. The augite is often of a violet tint and strongly pleochroic, and it is frequently bordered by hornblende in parallel position. The apatite is very abundant and builds large prisms. The analcime is in some cases secondary, and has been supposed to be derived from nepheline, while some observers have recorded the presence of nepheline

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[1] Watts, *Guide*, 78.

[2] A list of references to described examples is given by Kemp and Marsters, *Bull. No.* 107, *U. S. Geol. Sur.* (1893) 28, 29.

[3] *G. M.* 1888, 270, 271.

[4] J. A. Phillips, *Q. J. G. S.* (1876) xxxii, 155–178 ; (1878) xxxiv, 471–496, pl. xx–xxii.

in the rocks. A rock of teschenitic affinities is found at Car Craig in the Firth of Forth[1]. It is rich in a purplish brown, pleochroic augite, and contains altered felspar, analcime and other zeolites, iron ores, and brown mica (probably secondary). It presents points in common with the neighbouring picrite of Inchcolm. All these rocks are typically non-ophitic, but others more resembling normal diabases have also been included under the name teschenite. An analcime-bearing diabase of this kind forms a massive sill at Dippin in the south of Arran. It is a coarse-textured ophitic rock composed of olivine, apatite, magnetite, labradorite, purplish pleochroic augite, and clear interstitial patches of analcime. There is nothing to indicate that this last mineral is of other than primary origin. In San Luis Obispo County, California, Fairbanks[2] has described a diabase with analcime, which he finds to be in part primary.

[1] Teall, pl. xxii, fig. 1.
[2] *Bull. Dep. Geol. Univ. Calif.* (1895) i, 273–300, plate.

CHAPTER X.

LAMPROPHYRES.

The lamprophyres are a peculiar group of rocks occurring typically as dykes or other small intrusions. Chemically they are characterized by containing, with a medium or low silica-percentage, a considerable relative quantity of alkalies (especially potash), while the oxides of the diatomic elements are also abundantly represented. This shews itself in the commoner types of lamprophyres by an abundance of brown mica, and indeed the lamprophyres as a family are rich in ferro-magnesian silicates. They are fine-grained rocks, but almost always holocrystalline, and their structure is in some respects peculiar.

Von Gümbel's name lamprophyre has been extended by Rosenbusch to cover the various members of this family. The best known varieties are mica-lamprophyres ('mica-traps,' Ger. Glimmertrapp). Of these, two types have long been recognized, a chief point of distinction being the predominance of orthoclase in one and plagioclase in the other. To these types are given the names, respectively, *minette* (a word taken from the miners of the Vosges) and *kersantite* (from Kersanton, near Brest). To these Rosenbusch added two other types for rocks in which the place of biotite is taken by augite or hornblende. He separated those with dominant orthoclase (*vogesite*) from those with dominant plagioclase (*camptonite*). It should be noted that the criterion of the felspars does not lead in this family to a very natural division, especially when much of the potash in the rocks is present in mica. Further,

the decomposition of the rocks often renders the identification of the felspars difficult. For most purposes it is perhaps sufficient to distinguish the rocks merely as mica-, hornblende-, and augite-lamprophyres. There are other types of very basic composition, which are devoid of felspar, and these we shall group under the name *monchiquite*.

The rocks of this family have a wide range of chemical composition. Their equivalents, from this point of view, among the volcanic types are chiefly basaltic rocks, and especially leucite- and nepheline-bearing basalts. From these the lamprophyres as a whole differ considerably in mineralogical composition, olivine being wanting or poorly represented in many of the types, and the felspathoid minerals occurring only very exceptionally; while, on the other hand, brown mica, a mineral by no means characteristic of basaltic lavas, is a prominent constituent in many of the lamprophyres.

Constituent minerals. The characteristic mineral of those lamprophyres most usually met with is *biotite*, which occurs in hexagonal flakes. The extinction-angle (3° or 4°) is sufficient to shew frequently a lamellar twinning parallel to the basal cleavage. The flakes are very commonly bleached in the interior, retaining only at the margin the normal deep brown colour (fig. 31, *A*). With the bleaching there is a certain diminution in birefringence. More rarely we find a dark interior with a pale border, or a dark nucleus and border with a pale intermediate zone. Complete decomposition results in a pale, feebly polarizing substance as a pseudomorph. A greenish chloritic alteration is also found. Iron-oxide separates out, usually as limonite, and other minerals are produced as little wedges or lenticles along the cleavages of the mica (fig. 31, *A*). The titanic acid of the mica separates out as rutile, in fine needles arranged in three sets at angles of 60°: this is well seen in basal sections. The original inclusions of the biotite are apatite, and sometimes magnetite and zircon.

Short columnar crystals of *augite* occur in many lamprophyres, shewing sharp outlines with an octagonal cross-section, and sometimes lamellar twinning. When fresh, the mineral is pale green or almost colourless in slices, but it is readily replaced by serpentine, calcite, chlorite, *etc.*, in good pseudo-

morphs (fig. 31, *C*). In other cases uralitization may be noticed. The augite crystals are sometimes coated with flakes of biotite.
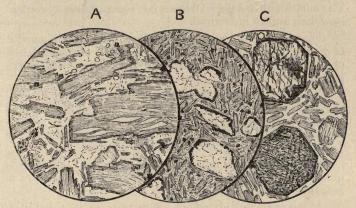
FIG. 31. MICA-LAMPROPHYRES; × 18.

A. Helm Gill, near Dent, Yorkshire. The mica-flakes shew each a dark border and a bleached interior. There are also lenticles of secondary products intercalated along the cleavage-planes [444].

B. Rawthey Bridge, near Sedbergh, Yorkshire. Olivine has been present in abundance, and is now replaced by some rhombohedral carbonate with a border of iron-oxide [2728].

C. St Heliers, Jersey. Shewing octagonal cross-sections of augite, largely replaced by secondary products [1094].

The most usual occurrence of *hornblende* is in long well-shaped prisms, frequently twinned, but it has some variety of habit. The colour is brown or sometimes green. The mineral may be converted into a chloritic substance with separation of iron-oxides.

A striking feature in the lamprophyres is that the felspars do not usually occur as phenocrysts. The nature of the felspar in the more altered rocks can be verified only after removing the carbonates from the slice with dilute acid. The small columnar or tabular crystals of *plagioclase* shew albite-lamellation and frequently zonary banding. They often have a kind of sheaf-like grouping. Decomposition, beginning in the

interior, gives rise to abundant calcite. The *orthoclase*, and perhaps anorthoclase, build short rectangular crystals, simple or carlsbad twins, often clouded or with ferruginous staining. The monchiquites have no felspar, but some apparently contain *analcime*, always interstitial.

Some of the more acid lamprophyres have a certain amount of *quartz*, which is either the latest product of consolidation or is intergrown with a portion of the felspar with micrographic structure.

A common accessory in some lamprophyres, and an essential in certain types, is *olivine*, which builds relatively large perfect crystals, or sometimes groups of rounded grains. It is occasionally found fresh, but very commonly represented by pseudomorphs of carbonates and serpentine (fig. 31, *B*).

The iron-ores are not often very abundant, and may be quite wanting. The most usual is *pyrites*, but octahedra of *magnetite* are also found.

A constant and abundant accessory is *apatite*, but it is sometimes in such fine needles as to be invisible except by oblique illumination. Sphene and zircon are only exceptionally met with.

Structures and peculiarities. Many of the lamprophyres are non-porphyritic, with a rather exceptional structure due to a strong tendency to idiomorphism of all the constituent minerals. This is the 'panidiomorphic' structure of Rosenbusch[1]. The porphyritic members of the family, again, have a peculiarity, in that the porphyritic character is produced by a recurrence of the ferro-magnesian constituents, not of the felspars. Any recurrence of the latter, and especially of orthoclase, is rare, but two generations of biotite or of hornblende are seen in many of the rocks. When olivine occurs, it is in conspicuous crystals, but only of one generation.

Without shewing any real flow-structure, the felspars of the rock sometimes have a special grouping in sheaf-like or rudely radiating fashion. Exceptionally orthoclase is moulded

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[1] See chromolithograph of kersantite in Berwerth, Lief. i; and of augite-minette in Lief. iii.

on the other constituents : usually it is idiomorphic, save when it builds micrographic structures with quartz. There is little indication of any isotropic residue in the typical lamprophyres, though in some cases little ovoid vesicles, filled with secondary products, suggest the former presence of some glassy matter, now perhaps devitrified. In some of the monchiquites, however, there is what has been described as a glassy base. The mica-lamprophyres are remarkably prone to decomposition, and often have 20 or 30 per cent. of calcite and other secondary products.

Grains of quartz and crystals of alkali-felspars are found, though very sparingly, in many lamprophyres. Their sporadic occurrence and, still more, some curious features which they invariably present compel us to regard them as something apart from the normal constitution of the rock and of quasi-foreign origin. The *enclosed quartz grains* are of rounded
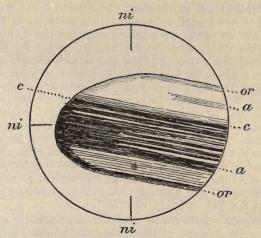
FIG. 32. OLIGOCLASE CRYSTAL ENCLOSED IN A LAMPROPHYRE DYKE AT GILL FARM, NEAR SHAP WELLS ; × 20.

Crossed nicols. The crystal is rounded by magmatic corrosion and bordered by a narrow margin of orthoclase (*or*). In addition to the albite-lamellation of the oligoclase (*a*), there is a carlsbad twinning (*c*) common to both felspars [1155].

form, with evident signs of corrosion, and are seen to be
surrounded by a narrow ring or shell due to a reaction
between the quartz and the surrounding magma. This shell
is probably in the first place of augite, but it is often found to
consist of minute flakes of greenish fibrous hornblende or of
calcite and chloritic products. The quartz having this mode
of occurrence must be distinguished from genuine derived
fragments torn from other rocks : these are of irregular form,
often complex, and may contain inclusions unknown in the
corroded quartz-grains.

The *enclosed felspar crystals* are always of an acid species
—either orthoclase or a plagioclase rich in soda. The crystals
are corroded so as to present a rounded outline, but not re-
duced to mere round grains. The plagioclase thus corroded
is bordered by a narrow margin of orthoclase due to the action
of the magma (fig. 32).

Illustrative examples. The best-known British ex-
amples occur as small dykes and sills in the north of England[1],
and are of an age between the Silurian and the Carboniferous.
The dykes are numerous in the southern part of the Lake Dis-
trict, from Windermere to Shap and on to Sedbergh, and they
are seen again in the Lower Palæozoic inliers of Ingleton, Eden-
side, and Teesdale. The rocks are *mica-lamprophyres,* but
many of them contain subordinate augite, always in perfect
crystals, but often decomposed. The relative proportions of
orthoclase and plagioclase vary, so that some examples would
be named minette and others kersantite, the latter being
perhaps the commoner. Good pseudomorphs after olivine are
seen in the dykes in the Sedbergh district (fig. 31, *B*). The
dykes at Cronkley, in Teesdale, have abundant pseudomorphs
with hexagonal and quadrangular outlines representing some
mineral not yet certainly identified.

Scattered quartz-grains with the characteristic corrosion-
border occur in many of the dykes ; and felspars, both ortho-
clase and oligoclase (fig. 32), are enclosed sporadically in the
Edenside intrusions, and more abundantly in those to the south
of the Shap granite. These rocks shew various transitions from
typical lamprophyres to a micaceous quartz-porphyry of one

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[1] *G. M.* 1892, 199–206, with numerous references.

of the less acid types, and indeed very different kinds of rocks occur imperfectly mingled in one and the same dyke.

Quartz does not occur as a normal constituent in most of the north-country lamprophyres, though it is found in the transitional rocks just mentioned. In an intrusion at Sale Fell, near Bassenthwaite, quartz occurs partly as interstitial grains, partly in micrographic intergrowth, and the rock shews considerable resemblance to the original kersantites of Brittany. The last-named rocks are sometimes even-grained, sometimes porphyritic ('porphyrites micacées' of Barrois).

Mica-lamprophyres are known also from the Isle of Man (Peel Castle), Galloway[1], the Cowal district of Argyllshire, Invernessshire (Farley near Beauly[2]), and some parts of Ireland.

An augite-bearing minette[3] seems to be one of the commonest types of lamprophyres. It is seen in Cornwall (Trelissick Creek, etc.), in the Channel Islands (Doyle Monument, Guernsey), and at numerous foreign localities (e.g. Plauen'scher Grund, near Dresden). With more abundant augite (e.g. Weinheim in the Odenwald) it passes into the augite-vogesites. The typical vogesites of the Vosges, etc., have sometimes augite, sometimes hornblende, as the dominant coloured constituent, the principal felspar being orthoclase.

In America mica-lamprophyres of the minette type have been described from Coanicut Island, R.I.[4], Franklin Furnace, N.J.[5], Nôtre Dame Bay in Newfoundland[6] (with accessory augite and hornblende), and the Sweet Grass Hills[7] (with augite) and Little Belt Mountains[8], Mont. The kersantite type is recorded from the Sierra Nevada region of California (Mariposa, Hamilton, etc.), and an augite-vogesite from the Black Hills of Dakota[9].

[1] Teall, Mem. Geol. Sur., Silur. Rocks Scot. (1899) 628, 629.

[2] Horne, M. M. (1886) vii, p. iv.

[3] Cohen (3), pl. xxiv, fig. 4 (Weinheim); Berwerth, Lief. iii (Schwarzenbach, Odenwald).

[4] Pirsson, A. J. S. (1893) xlvi, 374.

[5] Iddings, in Diller, 236–239.

[6] Wadsworth, A. J. S. (1884) xxviii, 99, 100.

[7] Weed and Pirsson, A. J. S. (1895) l, 313.

[8] Pirsson, 20th Ann. Rep. U. S. G. S., part iii. (1900) 526–531, pl. lxxvi, A.

[9] J. D. Irving, Ann. N. Y. Acad. Sci. (1899) xii, 287.

In the north-eastern United States and in Canada *hornblende-lamprophyres* of the camptonite type are widely distributed. The name was first applied by Rosenbusch to rocks described by Hawes[1] from Campton Falls, N.H., while closely similar rocks are found near Montreal[2], at Summit Station[3] and Mount Ascutney[4], Vt., at several points on the Hudson River highlands[5] and in the Lake Champlain district[6], and (with less abundant hornblende) at the Forest of Dean iron-mine, N.Y.[7] In all these idiomorphic brown hornblende, usually in two generations, is the chief constituent, felspar is subordinate, and augite is at most an accessory. In other varieties augite becomes prominent in addition to the dominant hornblende. When augite predominates, the rock may be termed augite-camptonite, but such rocks shew an approach to diabase by the augite losing its sharply idiomorphic habit.

Hornblendic lamprophyres, some more or less closely of the camptonite type, are found in various British localities. Some of the Warwickshire rocks originally described as diorites are camptonites, particularly one from Marston Jabet[8]. This contains abundant brown hornblende in idiomorphic elongated crystals. Some of these rocks carry porphyritic augite, and some contain olivine. Another district for camptonites is that of Beinn Nevis (Sgor Chalum, *etc.*[9]), and rocks more or less closely allied occur in Galloway (Black Gairy Hill[10]) and in the Cowal district of Argyllshire[11]. Some lamprophyre sills and dykes in the Assynt district of Suther-

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[1] *A. J. S.* (1879) xvii, 147–151 : also Iddings, in Diller, 239, 240 ; and see Berwerth, Lief. ii.

[2] Harrington, *Rep. Geol. Sur. Can.* 1878.

[3] Nason, *A. J. S.* (1889) xxxviii, 229.

[4] Jaggar, *Bull. No.* 148, *U. S. G. S.* (1897) 70.

[5] Kemp, *Amer. Naturalist*, 1888, 694–696, pl. xii.

[6] Kemp and Marsters, *Trans. N. Y. Acad. Sci.* (1891) xi, 21, 22 ; *Bull. No.* 107, *U. S. Geol. Sur.* (1893) 29–32.

[7] Kemp, *A. J. S.* (1888) xxxv, 331, 332.

[8] Allport, *Q. J. G. S.* (1879) xxxv, 638, 639 ; Watts, *Pr. Geol. Ass.* (1898) xv, 394 ; Teall, pl. xxix, fig. 2.

[9] Teall, *Summary of Progress, Geol. Sur.* for 1898, 48.

[10] Teall, *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) pl. xxv, fig. 2.

[11] Teall, *Mem. Geol. Sur. Scot., Geol. Cowal* (1897), 116–118.

land[1], except for the colour of their hornblende, are identical
with the camptonite type. They are characterized by abundant,
slender-twinned crystals of hornblende, sometimes of hollow
shape (fig. 33). In Ireland hornblendic, as well as micaceous,
lamprophyres are known from Galway, the Raphoe district, the
coast of Down, *etc.* Prof. Watts[2] describes one from Lettery,
near Clifden, as a camptonite, another from Clondermot, near
Raphoe, as a vogesite, and most of those in Co. Down carry
hornblende in addition to biotite.
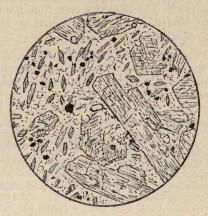
FIG. 33. HORNBLENDE-LAMPROPHYRE (APPROACHING CAMPTONITE), FROM
INTRUSIVE SILL IN DURNESS LIMESTONE, LOCH ASSYNT; × 20.

Shewing phenocrysts of green hornblende in a panidiomorphic ground-
mass of plagioclase and hornblende, with a little magnetite and apatite
[1687].

There remain the *monchiquites*, lamprophyric rocks of very
low silica-percentage and with a peculiar mineralogical com-
position. Felspar is absent, and instead there is a colourless
isotropic base of low refractive index, which was originally
regarded as a glass, but in some cases at least is found to be

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[1] Teall, *G. M.* 1886, 346–353.
[2] *Guide*, 53, 73–75.

analcime[1]. The other characteristic minerals are, in the typical rocks, olivine and augite, or in some varieties hornblende. Such rocks are known in Portugal, Brazil, Arkansas[2] and the Lake Champlain district[3]. Here too belong the rocks described in Montana under the name analcime-basalt[4]. A good example, with abundant analcime, has also been described from near Cripple Creek, Colorado[5]. The only British rocks of this type yet known are those described by Dr Flett[6] from the Orkney Islands. Here too occurs the rarer Fourche type, devoid of olivine, which is found in Arkansas[7] and the Lake Champlain district[8]. The Ouachita type, from the former area, is also without olivine, and is characterized by biotite as its dominant ferro-magnesian mineral[9].

It is to be observed that these various types, as well as the camptonites, are met with in association with nepheline-syenites and allied rocks, while the more usual mica-lamprophyres occur in connection with granites, etc.

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[1] Pirsson, *Journ. of Geol.* (1896) iv, 679–690 ; Evans, *Q. J. G. S.* (1901) lvii, 38–53.

[2] J. F. Williams, *Ign. Rocks Ark.*, vol. ii of *Rep. Geol. Sur. Ark.* for 1890, 151–157, 290–295, 353.

[3] Kemp and Marsters, *Trans. N. Y. Acad. Sci.* (1891) xi, 22, 23 ; *Bull. No.* 107, *U. S. Geol. Sur.* (1893) 32–35.

[4] Lindgren, *Proc. Calif. Acad. Sci.* (1896) iii, 51 (Highwood Mts) ; Weed and Pirsson, *Bull. No.* 139, *U. S. G. S.* (1896) 114–117 (Castle Mt.) ; Pirsson, *20th Ann. Rep. U. S. G. S.* part iii (1900), 543–550 (Little Belt Mts).

[5] Cross, *Journ. of Geol.* (1897) v, 684–693.

[6] *Trans. Roy. Soc. Edin.* (1900) xxxix, 887–896.

[7] J. F. Williams, *l.c.* 107, 108, 290.

[8] Kemp and Marsters, *l.c.* 35, 36.

[9] Kemp in *Ign. Rocks Ark.* 394–398.

C. VOLCANIC ROCKS.

Under this head we shall treat only the solid rocks of volcanic origin (lavas), reserving the fragmental products of volcanic action for the sedimentary group. With the true extruded lava-flows will be included similar rocks occurring in the form of dykes, *etc.*, in direct connection with volcanic centres, the common feature of all being that they have consolidated from fusion under superficial conditions, *i.e.* by comparatively rapid cooling under low pressure. This mode of origin has given the rocks as a whole characters which place them in contrast with the plutonic group, while the types treated above under the head of 'hypabyssal' have in some respects intermediate characters. Many volcanic outpourings have undoubtedly been submarine, and when these have taken place under a great depth of water the products may be expected to approximate in some measure to the characters of rocks of deep-seated origin. In general, however, the contrast between volcanic and plutonic types of structure is well marked.

The presence of a glassy (or devitrified) residue, though not peculiar to volcanic rocks, is highly characteristic of them, and especially of the more acid members. Other features characteristic of lavas, though not confined to them, are the vesicular and amygdaloidal structures, and the various fluxion-phenomena, including flow-lines, parallel orientation of phenocrysts, banding, drawing out of vesicles, *etc.*

The great majority of the volcanic rocks have a porphyritic structure, *i.e.* their constituents belong to two distinct periods of consolidation, the earlier represented by the porphyritic

crystals or 'phenocrysts'[1], and the later by the 'ground-mass,' which encloses them, and commonly makes up the bulk of the rock. This ground-mass may, and usually does, include some glassy residue or 'base': if the ground is wholly glassy, we have what is termed the 'vitrophyric' structure. The same mineral may occur both among the phenocrysts and as a constituent of the ground-mass. When such a recurrence is found, the crystals of the earlier generation are distinguished from those of the later by their larger size, often by their more perfect idiomorphism, and in some cases by fracture, corrosion, or other evidence of vicissitudes in their history. The two periods of consolidation are styled by Rosenbusch the 'intratelluric' and the 'effusive,' the former being considered as the result of crystallization prior to the pouring out of the lava, and so under more or less deep-seated conditions. When we speak of the consolidation of a lava at the earth's surface, we must be understood to refer to the ground-mass of the rock. In some few types of lavas the phenocrysts fail altogether, and the effusive period is the only one represented.

The various types will be grouped under families, to be taken roughly in order, beginning with the most acid. It is customary to speak of the several families of lavas as answering to the commonly recognized families of the plutonic rocks —the rhyolites to the granites, the trachytes to the syenites, *etc.*—but such a correspondence cannot be followed out with great exactness. It is certain that a given rock-magma may result in very different mineral-aggregates according as its consolidation is effected under deep-seated or under surface conditions ; and in the latter case, moreover, much of the rock produced may consist of unindividualised glass.

It is more especially in the volcanic rocks that the Continental petrologists have insisted upon a division into an 'older' and a 'younger' series ('palæovolcanic' and 'neovolcanic'), an arbitrary line being drawn between the pre-Tertiary lavas and the Tertiary and Recent. This distinction is rejected by the British school, and will find no place in the

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[1] This convenient term, due to Prof. Iddings, will be adopted here. Mr Blake has proposed the word 'inset,' as corresponding to the Ger. 'Einsprengling.'

following pages[1]. The simplified grouping of the volcanic rocks by their essential characters, without reference to their age or supposed age, involves some modification of the double nomenclature in use among the German and French writers. The names employed by them for the younger lavas only will here be extended to all rocks of the same character, irrespective of their geological antiquity. The names applied by the Continental writers to the pre-Tertiary lavas have also been used habitually for hypabyssal rock-types, and may now be restricted to these latter. Some of them (quartz-porphyry, porphyrite, diabase, *etc.*) we have already used in this sense.

[1] On this question see *Sci. Progr.* (1894) ii, 48–63.

CHAPTER XI.

RHYOLITES.

In the rhyolite family we include all the truly acid lavas ; rocks of porphyritic or vitrophyric structure, in which alkali-felspars and usually quartz figure as the chief constituent minerals. By the older writers most of these rocks were included, with others, under the large division 'trachyte.' The present family was separated by von Richthofen with the name 'rhyolite,' expressing the fact that flow-structures are commonly prominent in the rocks. Roth used the term 'liparite' in nearly the same sense. The Continental petrographers, following their regular principle, use these names for the Tertiary and Recent acid lavas only, the older (pre-Tertiary) being more or less arbitrarily separated and designated by other names (quartz-porphyry, porphyry, *etc.*); and some English geologists have tacitly adopted a like division, calling the older rhyolites, which have often suffered various secondary changes, quartz-felsites, felsites, *etc.*

Some petrologists distinguish between potash- and soda-rhyolites, according to the predominance of one or the other of the alkalies ; but in fine-textured or glassy rocks this difference does not always express itself in the minerals evident. There is, however, a peculiar group of acid lavas very rich in alkalies, and especially in soda : these rocks, the 'pantellarites' of Förstner, contain special characteristic minerals.

We shall consider briefly the characters of the phenocrysts or enclosed crystals and of the ground-mass. In some rhyolites

the phenocrysts occur only sparingly, or may even fail altogether.

Phenocrysts. Among the phenocrysts or porphyritically enclosed crystals of the rhyolites, the most constant are alkali-felspars; both *orthoclase* (including *sanidine*) in tabular or columnar crystals, simple or twinned, and an acid plagioclase, ranging from *albite* to *oligoclase*, in tabular crystals with the usual twin-lamellation. A parallel intergrowth of the monoclinic and triclinic species is occasionally found. The felspars often contain glass-[1] and gas-cavities, but rarely fluid-pores: such minerals as apatite, magnetite, biotite, *etc.*, may be sparingly enclosed. Certain rocks specially rich in soda (pantellarites, *etc.*) have *anorthoclase*.

Quartz, when present, occurs in dihexahedral crystals, often corroded and with inlets of the ground-mass. Besides occasional inclusions of minerals of early consolidation, it contains glass- but rarely fluid-cavities.

The more basic silicates are not present in great abundance. The most usual is *biotite* in deep-brown hexagonal flakes, with only occasional inclusions of apatite, zircon, or magnetite. A greenish *augite* with octagonal cross-section may be present, but brown *hornblende* is much less common. The pantellarites have the brown triclinic amphibole *cossyrite*, with intense absorption and pleochroism.

The most usual iron-ore is *magnetite*, but it is rarely abundant. Needles of *apatite* and minute crystals of highly refringent and birefringent *zircon* may also occur in small quantity. In rarer cases *garnet* is found instead of a ferro-magnesian bisilicate.

Ground-mass and structures. The rhyolites exhibit in their ground-mass a great variety of texture and structure. The texture may be wholly or partly glassy; or cryptocrystalline, often with special structures; or, again, evidently crystalline, though on a minute scale. Further, these several varieties of ground-mass may be associated in the same rock and in the same microscopical specimen. Fluxion is frequently marked by banding, successive bands being of different textures, so

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[1] Cohen (3), pl. IX, fig. 4.

that thin layers of glassy and stony or spherulitic nature altern-
ate with one another.

The *vitreous* type of ground-mass alone is found in the
obsidians[1]. These rocks, colourless or very pale yellow in
thin slices, afford good examples of structures common to all
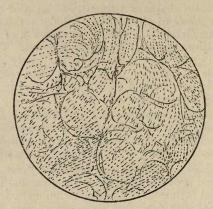
FIG. 34.   GLASSY RHYOLITE (OBSIDIAN), TELKIBANYA, NEAR
SCHEMNITZ, HUNGARY; × 20.

Shewing sinuous flow-lines traversed by a system of curving perlitic
fissures [G. 329].

the natural glasses; especially the *perlitic cracks* (fig. 34),
produced by contraction of the homogeneous material[2], and
the *vesicular* structure due to the rock-magma having been
distended by steam-bubbles. In extreme cases the cavities are
so numerous as to make up the chief part of the volume of the
rock, and we have the well-known pumice (Fr. ponce, Ger.
Bimstein). The vesicles are commonly elongated in the
direction of flow, and may even be drawn out into capillary

[1] The less common glassy rocks of the trachyte and phonolite family
and of the dacites are also termed obsidian. They are not easily distin-
guished from the rhyolite-glasses. Some of the rocks styled pitchstones
are lavas of the obsidian type, usually of acid composition (*e.g.* the
'Meissen pitchstones,' in Saxony).
[2] Cohen (3), pl. LXXI, figs. 1, 2.

tubes. In the older lavas vesicles are usually filled by secondary products, and become amygdules.

In many cases a ground-mass consisting essentially of glass
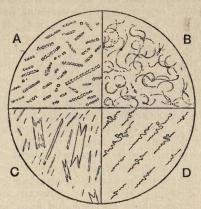
FIG. 35. CRYSTALLITES IN OBSIDIAN.
A. Margarites, Obsidian Cliff, Yellowstone Park; × 400 [477].
B. Trichites, Telkibanya, Hungary; × 100 [G. 327]. *C.* Longulites and swallow-tailed crystallites, Hlinik, Hungary; × 200 [G. 70].
D. Flow-structure marked by arrangement of twisted trichites, Prabacti, Java; × 200 [G. 64].

encloses minute bodies known as *crystallites* (fig. 35), which may be regarded as embryonic crystals[1]. They have definite forms, but no perfect crystal boundaries, and the more rudimentary types cannot be subjected to optical tests to determine their nature. The simplest effort at individualisation from the vitreous mass results in globulites, minute spherical bodies without action on polarized light. They occur in profusion in many obsidians, either uniformly distributed or aggregated into cloudy patches (cumulites). From the partial coalescence of a series of globulites, arranged in a line, result margarites[2], resembling strings of pearls. A high-power

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[1] See Rutley, *M. M.* (1891) ix, 261–271, and plate; Zirkel, *Micro. Petr. Fortieth Parallel*, pl. ix, figs. 1–4 ; Rosenbusch-Iddings, pl. ii, iii.
[2] Cohen (3), pl. vi.

objective (say $\frac{1}{8}$ inch) is often necessary to resolve this beaded structure. Long threads of this nature may extend in the direction of flow but with numerous little twists[1]. Similar threads with curved hair-like form, known as trichites, often occur in groups originating in a common nucleus. These bodies, in which a beaded structure may or may not be observable, often seem to belong to a stage of development later than the cessation of flowing movement in the mass[2]. The small rod-like bodies known as longulites, sometimes slightly clubbed at the ends[3], may be regarded as built up by the complete union of rows of globulites. They often occur in crowds, with a marked arrangement parallel to the direction of flow. The transition from margarites to longulites is often seen, some of the little rods resolving into beaded strings, while others do not. The larger crystallitic bodies termed microlites are possibly to be conceived as built up from longulites. Various incomplete stages may be observed, the ends of the imperfect microlites having a brush-like form (scopulites of Rutley) or being forked in swallow-tail fashion. Fully developed microlites have an elongated form, and are indeed small crystals giving the optical reactions proper to the mineral (felspar, augite, hornblende, *etc.*) of which they consist.

An original *cryptocrystalline* or 'microfelsitic' ground-mass is found in some rhyolites, though it seems to be more characteristic of intrusive types (approaching what we have styled quartz-porphyries) than of true surface lavas. It consists in a granular mixture of felspar and quartz on so minute a scale that the individual grains cannot be resolved in a thin slice. There is no doubt, however, that in many old acid lavas a cryptocrystalline ground-mass has resulted from the *devitrification* (Ger. Entglasung) of a rock originally vitreous. The process has often begun along perlitic fissures, or flow-lines, and the successive stages are beautifully displayed in such rocks as the Permian rhyolites ('pitchstones') of Meissen in Saxony. No single criterion can be set up for distinguishing an original from a secondary cryptocrystalline structure. In a rock

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[1] Zirkel, *Micro. Petrogr. Fortieth Parallel* (1876), pl. IX, figs. 3, 4.
[2] *Ibid.* figs. 1, 2.
[3] Fouqué and Lévy, pl. XVI, fig. 2.

otherwise fresh, however, there will generally be no reason to suspect devitrification; while, on the other hand, the presence of perlitic cracks is often taken to indicate that the rock in which they occur was originally glassy[1].

A *microcrystalline* (as distinguished from cryptocrystalline) ground-mass is not very prevalent in true acid lavas, but may occur as bands alternating with glassy or microspherulitic bands, often on a small scale. When an evident microcrystalline structure has been set up as a secondary alteration, it probably indicates, as a rule, something more than the merely physical change of devitrification. It is often connected with an introduction of silica from an external source, and in the resulting microcrystalline mosaic quartz often plays a more important part than it would do in a normal igneous rock. In some of the partly silicified Ordovician rhyolites of Westmorland a secondary quartz-mosaic still shews clear indication of former perlitic cracks, outlined by dust, as well as the characteristic banding. In these rocks, too, *silicification* has sometimes affected not only the ground-mass but the felspar phenocrysts.

Spherulitic and allied structures. The spherulitic growths which are common in many acid lavas may be conveniently divided into the larger and the smaller. Under the former head we have spherulites, often isolated, with diameters ranging from a fraction of an inch to several inches. They are best studied in certain obsidians, where they are usually of distinctly globular form and with well-defined boundary. The examples which have been most carefully examined, and may be taken as typical, consist mainly of extremely delicate fibres of felspar, arranged radially and on the whole straight, but often forked or branching[2]. In the spherulites of perfectly fresh rocks the space between the fibres is found to be occupied in great part by aggregates of tridymite. In older spherulites, where tridymite is not recognized, quartz may perhaps be

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[1] Some American writers have used the name ' aporhyolite ' for such devitrified rhyolites.

[2] See Cross, *Bull. Phil. Soc. Washington* (1891), xi, 411–414; Iddings, *ibid.* 445–464, with plates. Similar structures occur in dykes on Druim an Eidhne, near Loch Coruisk, Skye: see Judd, *Q. J. G. S.* (1893) xlix, pl. ii, iii.

considered to represent it.   In any case the structure is to be
made out only in carefully prepared and very thin slices.   It
may often be observed that the flow-lines of the lava pass
undisturbed through the spherulites, indicating that the latter
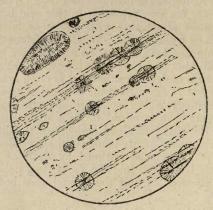
FIG. 36.   OBSIDIAN, VULCANO, LIPARI IS.; × 20.

The glassy matrix encloses isolated spherulites, with some tendency
to coalesce in bands following the direction of flow.   The flow-lines pass
uninterruptedly through the spherulites [1785].

crystallized after the cessation of movement.   Spherulites are
often developed along particular lines of flow, and may coalesce
into bands (fig. 36).

These larger spherulites shew many special peculiarities in
different examples.   Sometimes their outward extension has
been effected in two or more stages, which are marked by
a change in the character of the growth.   Again, curious
phenomena arise from the formation of shrinkage-cavities
(*lithophyses*) in connection with spherulites.   Some remarkable
examples of lithophyses have been described from the Yellow-
stone Park[1] and other districts in the United States[2], from

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[1] Iddings, *Obsidian Cliff*, in *7th Ann. Rep. U. S. Geol. Surv.* (1888)
265, 266, pl. xii–xiv ; *A. J. S.* (1887) xxxiii, 36–43.

[2] Nathrop, Colorado ; see Cross, *Proc. Colo. Sci. Soc.* (1886) 62–66.

Hungary, and from Lipari[1]. A peculiar feature is the occurrence in the hollows of perfect crystals of the iron-olivine (fayalite), as well as aggregates of tridymite, and in some cases crystals of garnet, topaz, *etc.* The complex forms of these lithophyses can be realised only from specimens or figures. They must be distinguished from ordinary ovoid vesicles.

The large spherulites are in some cases only skeleton-structures, the divergent rays being embedded in glass. Such *skeleton-spherulites*, in a devitrified matrix, have been described by Prof. Cole[2] in the 'pyromérides' of Wuenheim, in the Vosges.

Examination of the older acid lavas shews that the large spherulites are specially susceptible to certain chemical changes. They are often found partly or totally replaced by flint or quartz, while their insoluble decomposition-products remain as roughly concentric shells of a chloritic or pinitoid substance. Again, a central hollow is often found, and it is not always clear whether this is due entirely to decomposition or partly represents an original lithophysal cavity[3], nodular structures originating in both ways being represented in many districts.

The very minute spherulites commonly occur in large numbers, closely packed together, so as to constitute the chief bulk of particular bands, or even of the whole ground-mass of the rock. This is the *microspherulitic* structure[4]. The true nature of these very minute bodies, as composed of fine fibres of felspar with quartz, is a matter rather inferred than seen in any given case; but the radiate growth is detected by means of the 'black cross,' which each individual spherulite shews between crossed nicols (figs. 37, 38, *A*). These minute spherulites seem to be much less readily destroyed than the larger ones. The *axiolites* of Zirkel[5] seem to be of the nature of

[1] Cole and Butler, *Q. J. G. S.* (1892) xlviii, 438–443, pl. xii ; Johnston-Lavis, *G. M.* 1892, 488–491.

[2] *G. M.* 1887, 299–303.

[3] See especially Cole, *Q. J. G. S.* (1886) xlii, 183–190 ; (1892) xlviii, 443–445 ; Parkinson, *ibid.* (1901) lvii. 211–225, pl. viii.

[4] See Teall, pl. xxxviii.

[5] *Micro. Petr. Fortieth Parallel,* pl. vi, fig. 2. But compare Cole, *M. M.* (1891) ix, 271–274.

elongated spherulites, the fibres radiating not from a point but from an axis (fig. 38, *A*); or they may be conceived as
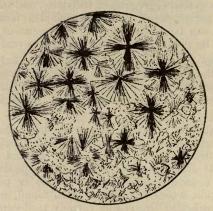
FIG. 37. MICROSPHERULITIC RHYOLITE, GREAT YARLSIDE, WESTMORLAND ; × 20, CROSSED NICOLS.

Each little spherule shews a black cross [1813].

representing the coalescence of a row of minute spherulites (*cf.* fig. 36).

Any evident micrographic structure is not common in the ground-mass of rhyolites, though bands or streaks having this character are sometimes found. A curious feature, first described by Iddings in some obsidians from the Yellowstone Park[1] and rhyolites from the Eureka district of Nevada[2], is the occurrence of porphyritic 'granophyre groups' or *micropegmatite phenocrysts* in a glassy, cryptocrystalline, or microcrystalline ground-mass (see fig. 38, *B*). In these the quartz is subordinate to the felspar in quantity, and the micrographic groups often shew the crystal-boundaries of the latter mineral. As a rule, however, there are several felspar crystals grouped together, the whole permeated by wedges of quartz, and the outline is complex or rather irregular.

[1] *7th Ann. Rep. U. S. Geol. Sur.* (1888) 274–276, pl. xv.
[2] *Monog.* xx *U. S. Geol. Sur.* (1893) 375, pl. v, fig. 2.

A structure met with in the ground of some rhyolites, and in certain bands of laminated rhyolites, differs essentially from
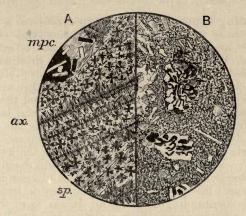
FIG. 38. SPECIAL STRUCTURES IN RHYOLITES, × 20; CROSSED NICOLS.

A. Falls of Gibbon River, Yellowstone Park : different bands, following the flow-lines, shew micropœcilitic (*mpc*), axiolitic (*ax*), and microspherulitic (*sp*) structures [1430]. *B.* Goodwick, near Fishguard, Pembrokeshire ; shewing micropegmatite phenocrysts in a finely micro-crystalline ground-mass [2289].

the micrographic, in that it indicates the successive, instead of simultaneous, crystallization of the two constituent minerals. Minute felspar crystals with no orderly arrangement are en-closed in little ovoid or irregular areas of quartz, the whole of the quartz in such a little area being in crystalline continuity. This structure reproduces on a minute scale the ophitic and pœcilitic structures presented by different minerals in other rocks, and Prof. G. H. Williams adopted for it the term *micro-pœcilitic*[1] (fig. 38, *A*).

An original holocrystalline texture on other than a minute scale is rarely, if ever, met with in true rhyolites. The 'nevadite' of Richthofen is exceptional in that the ground-mass

[1] *Journ. Geol.* (1893), i, 176–179.

is quite subordinate in quantity to the crowded phenocrysts, but this ground-mass is commonly glassy. In part, at least, these rocks belong to the dacites rather than the rhyolites.

Leading types. The glassy type (*obsidian*) is exemplified by many of the rhyolites of Iceland and of Lipari[1] (fig. 36); and in the latter locality pumice is extensively developed (Monte Chirica). The Hungarian rhyolites are not usually obsidians, but some good examples occur (Telkibanya)[2] with a rich variety of crystallites (fig. 35). Other well-known obsidians come from Ascension Is., Mexico, and the Yellowstone Park. The rock of Obsidian Cliff[3] in the last-named district frequently contains spherulites of some size, isolated or in bands, and remarkable chambered lithophyses, in which occur nests of tridymite and little crystals of the iron-olivine (fayalite). Very similar phenomena have been described from Lipari (Rocche Rosse)[4], and some of the Hungarian lavas also contain small lithophyses, often of hemispherical form, cut off by the fluxion-banding of the lava. It was there that these curious structures were first observed by von Richthofen (Telkibanya, Göncz, *etc.*).

The more widely distributed types of rhyolites may be studied in rich variety from the Tertiary volcanic districts of Schemnitz in Hungary, of the Lipari group, of the Western States of America, *etc.* They differ in the nature of their phenocrysts and in the structure of their ground-mass. Many of them have a strongly marked banded structure, successive narrow bands, a fraction of an inch wide, being of different textures or structures (glassy, microspherulitic, axiolitic, microcrystalline, micropœcilitic). The most usual ferro-magnesian mineral is biotite, but it is never plentiful.

When spherulitic structures are present they may be on a more or less minute scale. Some flows in the Schemnitz district are built up almost wholly of very diminutive spheru-

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[1] Cohen (3), pl. LXXII, fig. 3.
[2] Cohen (3), pl. LXXI, fig. 2.
[3] Iddings, 7*th Ann. Rep. U. S. Geol. Sur.* 249–295 ; and in Diller, 151–160, pl. XXV–XXVII.
[4] Cole and Butler, *Q. J. G. S.* (1892) xlviii, 438–445 ; Johnston-Lavis, *G. M.* 1892, 488–491.

lites[1], each giving a perfect black cross (Telkibanya, Sarospatak, Eisenbach, *etc.*). This microspherulitic type is also represented among the rhyolites of the Yellowstone Park[2]. In the typical 'perlites' of the Schemnitz district the individual spherulites are larger, with well-marked radial fibrous structure and globular form, sharply bounded, often by perlitic fissures (Hlinik, *etc.*). These contrast with a type in which the spherulites have an irregular outline, interlocking with one another or sending out processes into a glassy matrix.

Zirkel[3] described from Nevada rhyolites (including obsidians) shewing a remarkable variety in the character of their ground-mass. Others, from the Eureka district, have been described by Iddings[4]. These carry a little biotite. In examples described by the same author[5] from New Mexico (Tewan Mts) the ferro-magnesian mineral is augite. In these rocks plagioclase felspar is wanting : some contain spherulites and lithophyses. Rhyolites from Custer County, Colorado, have no coloured constituent except a little red garnet[6]. The ground-mass is usually microcrystalline to cryptocrystalline, but sometimes spherulitic. Biotite-bearing rhyolites with porphyritic quartz occur in the Tintic Mts, Utah[7]. Some varieties in the Lassen's Peak district, California, are highly spherulitic[8]. Examples from the Black Hills of Dakota have been described by Caswell[9], but Iddings[10] classes some of these rocks as dacites.

The best British examples of fresh Tertiary rhyolites are found in Antrim. Prof. Cole[11] has described lithoidal varieties

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[1] Fouqué and Lévy, pl. XVII, fig. 1.

[2] On obsidians and spherulitic rhyolites from the Yellowstone Park see also Rutley, *Q. J. G. S.* (1881) xxxvii, 391–396, pl. xx.

[3] *Micro. Petrogr. Fortieth Parallel* (1876), 163–205, pl. VI–IX.

[4] *Monog.* xx *U. S. Geol. Sur.* (1893) 374–380, pl. VIII; and in Diller, 160, 161.

[5] *Bull. No.* 66, *U. S. Geol. Sur.* (1890) 10, 11.

[6] Cross, *Proc. Colo. Sci. Soc.* 1887, 229–233.

[7] Tower and Smith, *19th Ann. Rep. U. S. Geol. Sur.* part III (1899), 633.

[8] Diller, *Bull.* No. 148, *U. S. Geol. Sur.* (1897) 192.

[9] *Geol. Black Hills* (1880), 486–488, *etc.*, pl. I, figs. 1, 2.

[10] *Ann. N. Y. Acad. Sci.* (1899) xii, 284–286.

[11] *Sci. Trans. Roy. Dubl. Soc.* (1896) vi, 77–118, pl. IV.

from Templepatrick, Cloughwater, and other places, and a good obsidian is found at Sandy Braes. In this last rock Prof. Watts[1] has remarked perlitic cracks traversing both the brown glassy ground-mass and the quartz phenocrysts. Other rhyolites occur between Dromore and Moira, Co. Down. In the Tertiary rhyolites of Fionn-choire, in Skye, the ground-mass is partly replaced by streaks and lenticles of quartz[2].

The most interesting British rhyolites, however, are those belonging to the Palæozoic and older volcanic groups, and these have doubtless had their pristine characters modified in many instances by secondary physical and chemical changes.

Mr Allport was the first to give a clear account of some of the old altered volcanic glasses, and to compare them with fresh Tertiary examples. He described what seems to be a devitrified and altered spherulitic rhyolite of pre-Cambrian age from Overley Hill or the Lea Rock near Wellington, Shropshire[3]. A few phenocrysts occur, but the bulk of the rock has been a glass enclosing numerous bands of spherulites. The glass is now devitrified, but perlitic cracks, marked by secondary products, are still evident. The spherulites too are for the most part much altered and stained red by iron-oxide.

The Ordovician rhyolites of Caernarvonshire[4] are characterized by the general paucity of any phenocrysts, and especially of those of quartz[5]. Among the scattered felspar-crystals, a member of the albite-oligoclase series predominates over ortho-clase. Almost the only ferro-magnesian constituent is a little colourless augite, and even this is commonly wanting, though a pale green decomposition-product may perhaps represent it. In all these features the rocks closely resemble the Tertiary and Recent rhyolites of Iceland, and probably the older rocks

[1] *Q. J. G. S.* (1894) 1, 367–375, pl. xviii.
[2] *Summary of Progress Geol. Sur.* for 1897, 132–134.
[3] *Q. J. G. S.* (1877) xxxiii, 449–460; Teall, pl. xxxiv, figs. 1, 2.
[4] *Bala Volc. Ser. Caern.* (1889) 18–23. See also Bonney, *Q. J. G. S.* (1882) xxxviii, 289–296, pl. x; Rutley, *ibid.* (1881) xxxvii, pl. xxi, and *Mem. Geol. Sur., Fels. Lavas* (1885), pl. ii–iv.
[5] This is true more especially of central and eastern Caernarvonshire. The rhyolites of the Lleyn peninsula, many of which are intrusive, are richer in phenocrysts, including quartz.

have once been largely glassy, as the younger are now. The usual texture of these old lavas is cryptocrystalline to micro-crystalline, sometimes shewing fluxion and banding, and oc-casionally good perlitic cracks. The vesicular structure is not very frequent. In some types the ground is partly micro-pœcilitic, minute felspar prisms being enclosed in quartz (Penmaenbach, *etc.*). Any approach to a microspherulitic structure of a perfect type is uncommon, but large isolated spherulites are abundant in many localities, and shew the various secondary alterations, concentric shell-structure, silici-fication, *etc.*, to which they are always prone[1]. The siliceous and other nodules which thus arise may reach several inches in diameter. Some of them probably represent true litho-physes[2].

Various types of rhyolites, including some with micro-pegmatite phenocrysts (fig. 38, *B*), occur in the Ordovician of Fishguard in Pembrokeshire[3]; spherulitic and other varieties on Skomer Island[4]; and imperfectly spherulitic types in the Precelli Hills[5]. Silicified rhyolites occur at Trefgarn and Roche Castle.

At Malvern (New Reservoir) occur cryptocrystalline (per-haps devitrified) rhyolites, sometimes enclosing scattered pheno-crysts of oligoclase. Narrow veins are occupied in some cases by infiltrations of calcite, in others by a clear mosaic of quartz, orthoclase, and plagioclase of secondary formation. Mr Parkinson[6] has described and figured ancient rhyolites with nodular structures representing altered lithophyses from Wrockwardine and Pontesford Hill in Shropshire, as well as from Boulay Bay in Jersey.

Nodular structures, often more or less completely replaced by quartz, are seen also in Westmorland (Great Yarlside). The

[1] *Bala Volc. Ser. Caern.* 35–39; Cole, *Q. J. G. S.* (1885) xli, 162–168, pl. IV, and (1886) xlii, 185–189, pl. IX; Miss Raisin, *ibid.* (1889) xlv, 247–269.

[2] Cole, *Q. J. G. S.* (1892) xlviii, 443–445, with references.

[3] Reed, *Q. J. G. S.* (1895) li, 162, pl. VI, figs. 3–5.

[4] Rutley, *Q. J. G. S.* (1881) xxxvii, 409–412; Howard and Small, *Trans. Cardiff Nat. Soc.* (1897) xxviii, part I, with plate.

[5] Parkinson, *Q. J. G. S.* (1897) liii, 465–476, pl. XXXVI.

[6] *Ibid.* (1901) lvii, 218–223, pl. VIII.

old rhyolites here resemble in many respects those of like age in Caernarvonshire, but certain flows shew a very perfect microspherulitic structure. This is well seen in Long Sleddale[1] and near Great Yarlside (fig. 37). From Dufton Pike, in Edenside, Mr Rutley[2] has described and figured rhyolites with a tufaceous structure ; and others from the same district shew flow brecciation or enclose foreign fragments[3].

Various acid lavas occur in the Ordovician of Ireland. Some from Raheen and other places in Co. Waterford shew perlitic and microspherulitic structures[4].

Ancient acid lavas of Palæozoic and pre-Palæozoic ages occupy large tracts in the east of Canada and the United States. In spite of alteration they have preserved many relics of original characteristic structures[5]. This is well illustrated by examples from South Mountain[6] (Penna.), which include micropœcilitic, spherulitic, lithophysal, brecciated, and other varieties. Ancient devitrified obsidians and rhyolites, some spherulitic, have been described from Vinal Haven[7] and North Haven[8] in Maine, from near St John, New Brunswick[9], from the Michigamme district in Michigan[10], etc.

Although we have not made a distinct subfamily of soda-rhyolites, it may be remarked that there are among the acid lavas some characterized by anorthoclase felspar and even soda-bearing pyroxene or amphibole. Some of the ceratophyres and quartz-ceratophyres of certain authors belong here. One

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[1] Rutley, *Q. J. G. S.* (1884) xl, pl. xviii, fig. 6, and *Mem. Geol. Sur.*, *Fels. Lavas* (1885), pl. ii, figs. 1, 2 ; Teall, pl. xxxviii [1921].

[2] *Q. J. G. S.* (1901) lvii, 31–37, pl. i.

[3] *Ibid.* (1891) xlvii, 518, 519.

[4] Reed, *Q. J. G. S.* (1899) lv, 763–766.

[5] G. H. Williams, *Journ. Geol.* (1894) ii, 1–31.

[6] G. H. Williams, *A. J. S.* (1892) xliv, 482–496 ; F. Bascom, *Journ. Geol.* (1893) i, 813–832, and *Bull.* 136 *U. S. G. S.* (1896) with plates. See also Diller, 343–349, pl. xliii, xliv.

[7] G. H. Williams, *Journ. Geol.* (1894) ii, 23 ; G. O. Smith, *Joh. Hopk. Univ. Circ.* No. 121 (1895), and *Geol. of Fox Is.*, *Me.* (1896) 46–51, pl. i, figs. 5, 6.

[8] Bayley, *Bull. Geol. Soc. Amer.* (1894) vi, 474.

[9] Matthew, *Trans. N. Y. Acad. Sci.* (1895) xiv, 197–200, pl. xii, xiii.

[10] Clements, *Journ. Geol.* (1895) iii, 811–817.

from Marblehead Neck, Mass., has phenocrysts of anortho-
clase[1]. Another from Baraboo Bluffs, Wis., is also rich in
soda[2]. An example from Berkeley, Cal., ranges from a
porphyritic variety with microcrystalline ground-mass to a
pure glass, but is usually microspherulitic[3].

An ægirine-bearing rhyolite is described by Bertolio from
Sardinia (Comende type). More remarkable are the rhyolites
of Pantellaria, an outlying island of the Lipari group, a
peculiar type rich in soda and iron (*pantellarite*). The pheno-
crysts are of anorthoclase and soda-sanidine, a green pleochroic
augite, and the deep-brown, intensely pleochroic cossyrite.
The ground-mass varies from almost holocrystalline to almost
wholly vitreous, a prevalent variety being a glass crowded
with microlites of the above-mentioned minerals. From the
Vieja Mts in Texas Lord[4] describes a quartz-pantellarite
with phenocrysts of anorthoclase, augite, and quartz in a
ground-mass of ægirine-augite, a brown hornblende (probably
barkevicite), orthoclase, and quartz.

[1] Sears, *Bull. Mus. Comp. Zool. Harv.* (1890) xvi, 162–172. *Cf.*
Washington, *Journ. Geol.* (1899) vii, 290–292.
[2] Weidman, *Bull. Univ. Wis.* (1895), *Sci. Ser.* i ; and in Diller, 164–
169, pl. xxviii.
[3] Palache, *Bull. Dep. Geol. Univ. Cal.* (1893) i, 61–72.
[4] *Bull.* 148 *U. S. G. S.* (1897) 96.

CHAPTER XII.

TRACHYTES AND PHONOLITES.

THE trachytes are lavas which, with a lower percentage of silica than the rhyolites, have as much or more of the alkalies. Consequently the typical *trachytes* consist essentially of alkali-felspars with a relatively small amount of coloured minerals and without free quartz. The name trachyte (given by Haüy to denote the rough aspect of the rocks in hand specimens) is used in the older literature to cover all the more acid half of the volcanic rocks. From it have been separated off, on the one hand, the rhyolites of modern nomenclature and, on the other, some hornblende- and mica-andesites, *etc.*

With the trachytes we shall treat some lavas of more peculiar constitution, in which a greater richness in alkalies has given rise to the formation of felspathoids as well as alkali-felspars : these are the *phonolites* and *leucitophyres.* The name phonolite (a translation of 'clinkstone,' from the supposed sonorous quality of the rock when struck) seems to have been in general use before the presence of microscopic nepheline in the rock was demonstrated, giving a character of precision to the definition. The original leucitophyres (of Coquand) were apparently any rocks with conspicuous crystals of leucite, but the name is now generally restricted to the types containing an alkali-felspar (sanidine) as an essential constituent. The leucitophyres are a type of extremely restricted distribution, and the unstable nature of the characteristic mineral must make such rocks difficult to detect

among the older lavas, a remark applicable also in some degree to the phonolites.

Constituent minerals. Felspars rich in potash or soda are by far the most abundant minerals in the rocks here considered. They occur both as phenocrysts and as the chief element in the ground-mass. The most prominent is usually orthoclase of the *sanidine* variety, often shewing a rough ortho-pinacoidal cleavage[1]. In phenocrysts it has either a tabular or a columnar habit, and both may occur in the same rock. Carlsbad twinning is frequent[2], and in the larger crystals may shew the broken divisional line due to interpenetration. Some degree of zonary banding is sometimes found. The plagioclase felspar which occurs in many trachytes is usually *oligoclase*, but in more basic rocks we may find varieties richer in lime instead. The phenocrysts often shew carlsbad- as well as albite-twinning; zonary banding is not uncommon; and parallel intergrowth with sanidine may be noted[3] (fig. 39, *B*).

In the true trachytes the most common ferro-magnesian element is perhaps brown *biotite*, in hexagonal flakes almost always affected by corrosion by the enclosing magma ('resorption'). This is shewn by a certain degree of rounding and the formation of a dark or opaque border, or even the total destruction of the flake, the resulting products being especially magnetite and sometimes greenish augite in minute granules. The frequent preservation of the original crystal-forms proves that the process is not one of fusion and re-crystallization, but rather pseudomorphism depending on changed physical conditions and chemical reactions with the fluid magma[4]. Brown *hornblende* is a less frequent constituent, in idiomorphic crystals with similar resorption-phenomena. The *augite*, which is scarcely less common than biotite as a constituent of trachytes, never shews this feature. It is usually pale green in thin slices. In the phonolites and leucitophyres the crystal often shews a deeper tint at the margin, and is almost always sensibly pleochroic (ægirine-

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[1] Cohen (3), pl. xlvii, fig. 3.
[2] *Ibid.* pl. xxiv, fig. 1.
[3] *Ibid.* pl. xxxii, fig. 3.
[4] Washington, *Journ. Geol.* (1896) iv, 257–282.

augite), a character less common in the trachytes. The soda-pyroxene, *ægirine*, is characteristic of many phonolites and leucitophyres, but only occasionally present in the trachytes. It is green and pleochroic, with a much lower extinction-angle than the augites (5° or less in longitudinal sections). It sometimes grows round a kernel of augite with parallel orientation. The rhombic pyroxene of certain trachytes is always of a deeply coloured and vividly pleochroic variety (*hypersthene* or *amblystegite*), giving red-brown, yellow-brown, and green colours for the several principal directions of absorption.

The *nepheline* of the phonolites and leucitophyres occurs in minute crystals in the ground-mass, having the form of a short hexagonal prism with basal planes, and giving squarish or hexagonal sections (fig. 40, *A*). Owing to the small size of the crystals and the optical properties of the mineral, it is liable to be overlooked. Its decomposition gives rise to various soda-zeolites, which occur in nests and veins in many phonolites. The *leucite* of the leucitophyres is always idiomorphic, giving characteristic octagonal and rounded sections (fig. 40, *B*). Twin-lamellation is very frequent in the phenocrysts[1], but the smaller crystals which may occur often behave almost as if isotropic. The leucite may enclose needles of augite and crystals of the earlier-formed minerals, but not of felspar. Minerals of the sodalite group are found in certain trachytes and constantly in the phonolites and leucitophyres. They are almost always in idiomorphic dodecahedra. The *sodalite* is clear when fresh, but often turbid from alteration : zonary structure is frequent. The blue *haüyne* is less often met with, but *nosean* may be very plentiful, usually forming crystals of some size, and always shewing more or less plainly its characteristic structure and border[2] (fig. 40, *B*). The sodalite-minerals give rise by alteration to natrolite and other zeolites.

Iron-ores (*magnetite*) occur but sparingly in these rocks. Yellowish *sphene* in good crystals is highly characteristic ; and *apatite* is common in colourless needles or sometimes in rather stouter prisms with violet dichroism. The trachytes often contain a little *zircon* in minute prisms.

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[1] Cohen (3), pl. xxviii, fig. 4.   [2] Teall, pl. xli, fig. 1; xlvii, fig. 4.

Among less common minerals may be mentioned the *tridymite* of certain trachytes, in aggregates of minute flakes; *olivine*, as a rare constituent except in certain basic trachytes; and *melanite* garnet, which is found in some of the leucitophyres and in certain phonolites as brown isotropic crystals belonging to an early stage of consolidation, sometimes shewing marked zonary banding.

As secondary products in trachytic (as also in andesitic) rocks, *opal* and other forms of soluble silica are not uncommon. Normally isotropic, these substances sometimes shew double refraction as a consequence of strain, usually about centres, so as to imitate a spherulitic structure. Opal sometimes encloses little flakes or aggregates of tridymite, or is coloured red by included scales of hæmatite. It occurs in the form of veins and irregular knots or patches. Aggregates of minute scales of *tridymite* are common in certain trachytic lavas, such as the 'domites' of Auvergne[1].

Ground-mass. In contrast with the rhyolites, the rocks under consideration have few glassy representatives, and the ground-mass is frequently holocrystalline, or at least with no sensible amount of glassy residue. This is especially true of the typical trachytes, which, with a chemical composition not very different from that of a mixture of felspars, have a strong tendency to crystallize bodily. Fluxional phenomena are not conspicuous, and the characteristic banding of the rhyolites is here wanting. Vesicular structure is rare, and perlitic cracks are not formed; but, in consequence of the crystalline nature of the ground, with a tendency to idiomorphism in its elements, a miarolitic or drusy structure may be met with. Any structure comparable with the spherulitic is uncommon, though a rough radial grouping of felspar prisms is sometimes observable.

Excepting the nepheline of the phonolites, non-felspathic constituents play in most cases a small part in the ground-mass of the rocks here considered. The ground consists, in the trachytes proper, essentially of minute felspars, which may, however, vary somewhat in habit. Most commonly they are

[1] Cohen (3), pl. xxxvii, fig. 1.

'lath-shaped' microlites, with some degree of parallel dis-position in consequence of flow, and this type of ground is so characteristic of these rocks that it is often styled the *trachytic*[1]. On the other hand the minute felspars may have a shorter and stouter shape, recalling some of the rocks grouped above under the porphyries, and this structure is accordingly designated by Rosenbusch the *orthophyric*[2] (fig. 39).

Phonolites poor in nepheline do not differ essentially as regards structures from the trachytes; but when the character-istic mineral is plentiful, forming very numerous minute crystals in the ground-mass, the general aspect of the latter is somewhat altered. The leucitophyres shew in their very variable structures further departures from the trachyte type, and the porphyritic character is sometimes lost; but all the rocks included in the present chapter resemble one another in being normally holocrystalline.

Leading types. Among the best known foreign *trachytes* are those of the Siebengebirge (Drachenfels type). Here a ground-mass of lath-shaped felspar microlites, with typical trachytic structure, encloses crystals of sanidine and oligoclase. The former are frequently of large size, and may shew carlsbad twinning. Biotite and magnetite occur sparingly. The rock of Perlenhardt in the same district exemplifies what Rosen-busch styles the orthophyric type of ground-mass. A little green augite accompanies the biotite, sphene is common, and sodalite occurs in crystals or in crystalline patches. In America a trachyte of the Drachenfels type has been described by Cross[3] from the neighbourhood of Rosita in Colorado, and similar rocks are found in the Black Hills of Dakota[4].

Trachytes from Solfatara and Mte Olibano[5] resemble generally the Perlenhardt rock. Numerous augite-trachytes are found in the neighbourhood of Naples and the Phlegræan Fields[6]. In Britain some very fresh augite-bearing trachytes

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[1] Berwerth, Lief. I. (augite-trachyte, Naples).
[2] *Ibid.* Lief. II. (domite, Auvergne).
[3] *Proc. Colo. Sci. Soc.* 1887, 234 ; and in Diller, 181, 182.
[4] Caswell. *Geol. Black Hills* (1880), 488–492, *etc.*, pl. II.
[5] Cohen (3), pl. xv, fig. 2.
[6] Berwerth, Lief. I.

occur as lava-flows and volcanic necks of Lower Carboniferous age in the Garlton Hills, Haddingtonshire[1]. These rocks consist of alkali-felspars with more or less of a bright to pale green pleochroic augite, doubtless a soda-bearing variety. Specimens from Peppercraig (fig. 39) shew phenocrysts of sanidine, sometimes with intergrowths of oligoclase, in a holocrystalline ground-mass. The latter is chiefly of sanidine prisms, with a minor proportion of striated felspar. Augite builds imperfect crystals and grains and numerous smaller granules; magnetite occurs sparingly in the same manner; and occasional needles of apatite are seen. Trachytes of Old Red Sandstone age are found in the neighbourhood of Melrose. Some of these contain no mineral of the ferro-magnesian division. One from Easter Eildon Hill is described by Mr Barron[2] as carrying riebeckite.
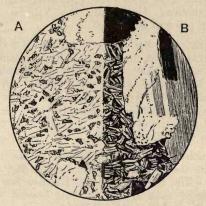
FIG. 39. AUGITE-TRACHYTE, PEPPERCRAIG, HADDINGTON; × 20.

A in natural light, *B* between crossed nicols. Large phenocrysts of felspar are enclosed in a ground composed entirely of little felspar prisms and granules of augite [1980]. The structure is orthophyric.

[1] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 115–126; see also Geikie, *ibid.* (1879) xxix, pl. XII, figs. 1, 2. The Carboniferous trachytes described by McMahon from Dartmoor seem to be much altered and their characters obscured; *Q. J. G. S.* (1894) l, 345, 346.

[2] *G. M.* 1896, 376.

In those trachytes which in some respects approach the andesites, the coloured constituents, especially pyroxene, become relatively abundant, and plagioclase begins to predominate over orthoclase among the phenocrysts. A type from Mte Amiata in Tuscany and M. Dore in Auvergne contains a vividly pleochroic rhombic pyroxene (amblystegite) with subordinate biotite. Garnet and tridymite are accessories. The ground-mass of these rocks is of very variable character, even in the same flow, and is sometimes largely glassy. Washington[1] has proposed the name vulsinite for a group of rocks intermediate between trachyte and andesite. They contain a considerable amount of a basic plagioclase in addition to the alkali-felspar, and the ferro-magnesian constituent is typically augite. In examples from Bolsena in Italy the phenocrysts are of alkali-felspar, anorthite, augite, and biotite, and the ground-mass is of soda-orthoclase, augite, etc., with trachytic structure. One from the Viterbo district has labradorite in place of anorthite.

A somewhat more basic type, from the Mti Cimini in the latter district, is styled ciminite[2]. It has the same association of sanidine with a basic felspar, but carries phenocrysts of olivine, as well as of augite and felspar. A well-known example of this is the Arso trachyte, the Ischia lava of A.D. 1302, which approximates in some features to the basalts. The ground-mass is of felspar microlites with interstitial glass, and is sometimes vesicular.

Other trachytes shew an approach to the characters of phonolites in the abundance of sodalite, the ocurrence of ægirine, etc. The trachytes of the Laacher See in the Eifel have crystals of sodalite and haüyne, besides sanidine and oligoclase. Biotite, brown hornblende, ægirine, sphene, magnetite, etc., also occur, and the ground-mass is of the trachytic type. At the Laach volcano are found also ejected blocks of a rock named sanidine-trachyte or sanidinite. This consists essentially of sanidine with subordinate oligoclase, sodalite, occasional biotite, etc. Stellate groupings of crystals occur

[1] Journ. Geol. (1896) iv, 547–554, 833.
[2] Journ. Geol. (1896) iv, 834–838, and (1897) v, 354.

in both felspars, but on the whole the structure is that of a plutonic (syenitic) rather than a volcanic rock.

While the dominant mineral of the trachytic lavas is commonly a potash-felspar, there are some types very rich in soda ; albite, anorthoclase, or some allied felspar occurring almost to the exclusion of sanidine or orthoclase. The 'quartz-less pantellarites' of Pantellaria must be placed here, and the older equivalents of such types are to be sought among some of the rocks which have been styled quartzless cerato-phyres. A very interesting soda-felspar-rock has been described from Dinas Head on the north coast of Cornwall[1]. This is possibly to be regarded as an ancient lava[2], and it consists almost wholly of albite. Besides a compact variety, there are others which are spherulitic and nodular. The centre of a spherule is cryptocrystalline, while its outer portion consists of radiating blades of albite. Such rocks may be termed old soda-trachytes, corresponding with the soda-rhyolites which are also known in this country. Lavas consisting almost wholly of alkali-felspars occur at Hamilton Hill and other places near Peebles[3]. Small felspar phenocrysts are embedded in a felspathic ground-mass of microlitic or cryptocrystalline structure, and analysis shews that soda-felspar largely pre-dominates.

Purely glassy varieties (trachyte-obsidians) are uncommon in this family. In the localities where they are found, they are associated with trachytes wholly or mainly crystalline, or even narrow alternating bands occur of pure glass and of trachyte largely microcrystalline. Good examples of this occur in the Peak of Tenerife. It may be noted that a glassy variety of phonolite also is found in the Canaries, usually as a slaggy crust on the surface of a lava-flow. It is a brown or yellow glass with little development of crystallites.

Coming now to the *phonolites*, we notice first those in which nepheline is only sparingly present, and which thus stand in close relation with the trachytes. Such rocks, the

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[1] Howard Fox, *G. M.* 1895, 13–20.

[2] McMahon, however, regards it as a metamorphosed sediment ; *ibid.* 257, 258.

[3] Teall, *Ann. Rep. Geol. Sur.* for 1896, 40.

'trachytoid' phonolites of Rosenbusch, are not the most characteristic type ; and the 'nephelinitoid' group, in which the special mineral of the phonolites is more abundantly present, is commoner. Some of the Saxon phonolites are of the trachytoid type (Olbersdorf, near Zittau). A good example is found at Traprain Law in association with the trachytes of the Garlton Hills, Haddingtonshire[1], and is of interest as being of Carboniferous age. It consists essentially of a mass of little sanidine prisms, with a fluxional arrangement, in which lie ragged crystals of a bright green soda-augite. Small colourless patches are found on very close examination to consist of little crystals of nepheline with zeolitic decomposition-products. A lava from Middle Eildon Hill, near Melrose, is also a phonolite of trachytoid type, and is remarkable for having riebeckite instead of ægirine. The mineral occurs, as usual, in irregularly shaped patches, moulded on the felspar. This rock is of Upper Old Red Sandstone age[2].

Of the commoner type of phonolite good examples occur in Bohemia[3] (Brüx, Teplitz, Marienberg, etc.), sanidine, nepheline, and ægirine being the essential minerals. Some varieties have conspicuous phenocrysts of sanidine. At the Roche Sanadoire[4] in Auvergne the porphyritic sanidines have often a core of plagioclase in parallel intergrowth, and little lath-shaped crystals of plagioclase occur also in the ground-mass.

Another British phonolite—that of the Wolf Rock off the coast of Cornwall—is also a good example. It belongs to the nosean-phonolites of some authors, that mineral being found plentifully in it, in addition to nepheline. The nosean occurs chiefly as phenocrysts with a dark interior and clear border[5]. Sanidine is also found as phenocrysts. The general mass of the rock consists of lath-shaped sanidine crystals, more or less idiomorphic crystals of nepheline, and little, dirty green microlites of ægirine. Iron-ores are scarcely represented, and there is little or no residual glass.

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[1] Hatch, G. M. 1892, 149 ; Trans. Roy. Soc. Edin. (1892) xxxvii, 124.
[2] Barron, G. M. 1896, 373-375.
[3] For chromolithograph see Berwerth, Lief. IV (Brüx).
[4] Fouqué and Lévy, pl. XLVII, fig. 1 ; cf. fig. 2 and pl. XLVI.
[5] Teall, pl. XLVII, fig. 4 (misplaced 5 in key-plate).

Phonolites are only sparingly represented among the varied volcanic rocks of the United States. One from El Paso County, Colorado[1], is essentially a finely granular aggregate of sanidine, nepheline, and hornblende, with phenocrysts of the two former minerals. A similar rock, with the addition of a little nosean, is known from Black Butte in the Black
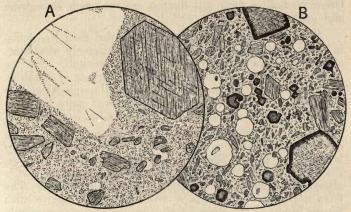
Fig. 40 ; × 20.

A. Phonolite, Black Hills, S. Dakota. Phenocrysts of soda-sanidine and ægirine in a ground-mass of nepheline and sanidine [3072].

B. Leucitophyre, Burgberg, near Rieden, Eifel. Phenocrysts of green ægirine-augite, dark-bordered nosean, and clear leucite in a ground-mass of ægirine-augite, nepheline, and sanidine [G. 120].

Hills of Dakota[2]. The felspar phenocrysts are of soda-ortho-clase or anorthoclase[3]. Phonolites occur as volcanic dykes and larger masses in the Cripple Creek mining district, Colorado[4]. They are rich in alkali-felspars, and contain phenocrysts of soda-sanidine or anorthoclase. Nepheline occurs with variable

[1] Cross, *Proc. Colo. Sci. Soc.* 1887, 167, 168.
[2] Caswell, *Geol. Black Hills, U. S. G. and G. Sur. Rocky Mts* (1880), 503–505, pl. I, figs. 3, 4 ; Cross in Diller, 191–193.
[3] Pirsson, *A. J. S.* (1894) xlvii, 341–346.
[4] Cross, *16th Ann. Rep. U. S. Geol. Sur.* part II (1895), 25–36.

habit, sometimes building small phenocrysts, while porphyritic nosean and minute crystals of sodalite are also found. Ægirine and ægirine-augite are the coloured minerals, or in certain cases a blue amphibole, and among the accessory minerals is analcime, believed to be of primary origin. Osann's rocks from western Texas (Apache type) are rich in hornblende, including a blue variety, and the felspars shew microperthitic intergrowths. Other phonolites from this district are very rich in ægirine and nepheline [1].

A remarkable phonolitic rock is recorded from Kosciusko in New South Wales [2]. Nepheline is extremely abundant, and occurs in microporphyritic idiomorphic crystals. Ægirine is also abundant, but there are no phenocrysts of sanidine. There is a small amount of glassy base, through which are scattered microlites of felspar. Phonolites of more than one variety occur in the neighbourhood of Dunedin, New Zealand [3].

The *leucitophyres* [4] are a very small group of rocks, known only from a few districts, and best developed in the late Tertiary lavas of the Eifel. The leucite is often of two generations, the larger crystals being frequently of irregular shape. It is always accompanied by nosean and sanidine (fig. 40, *B*). The ferro-magnesian mineral is a green pleochroic augite with zonary banding : the other constituents are sphene, occasionally biotite, and often a little melanite. The structure of the rocks is very variable. In some there is a well-defined ground-mass of minute nepheline, sanidine, augite, and leucite, enclosing phenocrysts of leucite and nosean (Olbrück, *etc.*). In other varieties there is but little sanidine (Schorenberg), while others again have sanidine in large shapeless plates enclosing the other constituents instead of a ground-mass (Perlerkopf). Leucitophyres shewing some variety of characters occur at several volcanic centres in Italy [5].

[1] Osann, 4th *Ann. Rep. Geol. Sur. Tex.* (1892) 130, 131.

[2] Guthrie, David, and Woolnough, *Roy. Soc. N. S. W.* (1901).

[3] Ulrich, *Trans. Austral. Ass.* (1891) iii, 127–150, pl. v.

[4] For figures see Berwerth, Lief. iv; Cohen (3), pl. ii, fig. 3, iv, fig. 3, and xvi, figs. 1, 2 ; Fouqué and Lévy, pl. xlviii, fig. 1 and li, fig. 1 ; Teall, pl. xli, fig. 2 and xlvii, fig. 4.

[5] Washington, *Journ. Geol.* (1896) iv, 559–561 (Bolsena), 840–845 (Viterbo) ; (1897) v, 43 (L. Bracciano), and 248, 249 (Rocca Monfina).

CHAPTER XIII.

ANDESITES.

In this family we include all the lavas of 'intermediate' composition not embraced in the preceding chapter. The name andesite, first used by von Buch and derived from the prevalence of such rocks in the Andes[1], is roughly equivalent to Abich's 'trachydolerite,' implying the intermediate position of these lavas between the acid ones (trachytes of older writers) and the basic (dolerites). The characteristic minerals are a soda-lime-felspar and one or more ferro-magnesian minerals. The alkali-felspars and quartz of the acid rocks are typically absent, as are also the lime-felspar and olivine of the basic rocks. The andesites are distinguished, according to the dominant ferro-magnesian constituent, as *hornblende-*, *mica-*, *augite-*, and *hypersthene-andesites*. Further there is usually recognized a quartz-bearing and more acid division, known as *dacites* or quartz-andesites. Having regard to true lavas, these quartz-bearing andesites seem to be of somewhat limited distribution : many of the rocks described as 'dacites' are of hypabyssal types, and belong to the less acid quartz-porphyries.

Those petrologists who restrict the name andesite to rocks of late geological age, apply to their pre-Tertiary equivalents the name 'porphyrite[2].' Under the same title they include

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[1] It should be remarked, however, that the early usage of the word was different, or at least wider, including rocks of plutonic habitus (quartz-diorites).

[2] Many also of the rocks designated 'melaphyre' are pyroxene-andesites, others being basalts.

various rocks of hypabyssal types, and it is to these latter that we have already confined the name. Again, certain English petrologists have used the name 'porphyrite' for andesites which have undergone some degree of change by weathering, *etc.*, a distinction which seems scarcely important enough to be recognized in classification or nomenclature.

As regards the general affinities of the family, the dacites have features in common with the rhyolites, the hornblende- and mica-andesites with the trachytes, and the pyroxene-andesites with the basalts, marking thus the intermediate position held among the volcanic rocks by the lavas here considered. As regards the appropriateness of the name, it is remarkable that the lavas of the great volcanic belt of the Andes belong, in so far as they are known, almost exclusively to this family[1].

Phenocrysts. Soda-lime-felspars are the most abundant elements porphyritically developed in these rocks. They include members varying from oligoclase to anorthite, but *andesine* and *labradorite* are the most common. As a rule, the more acid plagioclase belongs to the hornblende- and mica-andesites and dacites, the more basic to the pyroxene-andesites[2]. The crystals, however, are often strongly zoned[3] (fig. 41, *B*), shewing a change from a more basic variety in the centre to a more acid at the margin. They are idiomorphic and of tabular habit. With albite-lamellation is frequently associated twinning on the pericline or on the carlsbad law. The commonest inclusions are glass-cavities[4], either as 'negative crystals,' or rounded : sometimes large irregular cavities occupy much of the bulk of a crystal[5]. The decomposition-products of the felspars are calcite, finely divided kaolin or mica, epidote, quartz, *etc.* When an alkali-felspar occurs as

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[1] *Cf.* Iddings, *Journ. Geol.* (1893) i, 164–175.
[2] French petrologists recognize ' andesites ' and ' labradorites ' as distinct groups, characterized by andesine and labrador-felspar respectively, but this is with reference to the ground-mass.
[3] Iddings, *Monog.* xx *U. S. Geol. Sur.* (1893) pl. v, figs. 1, 3, 4 ; vi, fig. 2.
[4] See Zirkel, *Micro. Petr. Fortieth Parall.* pl. v, fig. 3 ; xi, fig. 2.
[5] Cohen (3), pl. viii, fig. 1.

an accessory, it has the same characters as in the rhyolites and trachytes.

The *hornblende* of andesites is in idiomorphic prisms, often twinned. It is usually a brown pleochroic variety with quite low extinction-angle, but green hornblende also occurs. The mica is a brown, strongly pleochroic *biotite*, with extinction sometimes sufficiently oblique to shew lamellar twinning parallel to the base. Both hornblende and biotite shew the same resorption-phenomena[1] as in the trachytes. It is possible that some part of the finely divided magnetite and granular augite in the ground-mass of certain andesites comes from the breaking up of hornblende altered in this way[2]. By decomposition of the ordinary kind the hornblende and mica of andesites give rise to chlorite, magnetite, carbonates, *etc.*

The *augite* is in well-shaped crystals, light green and usually without sensible pleochroism. Twin-lamellation is common. Alteration may give rise to chlorite, epidote, calcite, *etc.* The rhombic pyroxene in the andesites is usually *hypersthene*[3], or at least a distinctly coloured and more or less pleochroic variety. It builds idiomorphic crystals, in which the pinacoid faces are more developed than the prism; so that the cross-section is a square with truncated corners, as contrasted with the regular octagon of augite. In longitudinal sections the straight extinction is of course characteristic. The rhombic pyroxene is often converted in the older rocks to bastite.

The *quartz* of the dacites is either in good hexagonal pyramids or more or less rounded and corroded, with inlets of the ground-mass.

Original iron-ores are usually not abundant: *magnetite* is the only one commonly found. Needles of *apatite* occur, and in the more acid andesites little *zircons*[4]. Some of the more

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[1] Fouqué and Lévy, pl. xxviii, xxix; Zirkel, *Micro. Petrogr. Fortieth Parallel*, pl. v, fig. 2.

[2] Washington, *Journ. Geol.* (1896) iv, 273–278.

[3] Cross, *Bull. No. 1 U. S. Geol. Sur.* (1883); *A. J. S.* (1883) xxv, 139; Teall, *G. M.* 1883, 145–148.

[4] Iddings, *Monog.* xx *U. S. Geol. Sur.* (1893) pl. iii, figs. 15–20.

basic rocks have sparingly phenocrysts of *olivine*. As occasional accessories may be noted *tridymite*[1] (in druses), *garnet,* and *cordierite.*

Structure of ground-mass. In many andesites the only mineral which occurs distinctly in two generations is the felspar. The felspar of the ground-mass builds little 'lath-shaped' crystals, often simple, sometimes twinned, but usually without repetition. It is probably, as a rule, of a more acid variety than the porphyritic felspar, andesine or oligoclase occurring in different cases. Augite also may be present as a constituent of the ground-mass, forming very small crystals of pale-green tint.

Some of the hornblende- and mica-andesites have a *trachytic* type of ground-mass, composed essentially of very small felspar-laths with little or no glassy base, as in the Drachenfels trachyte. It is not always easy to ascertain whether any glass is present or not. From this type, as from the others, there are, however, transitions to rocks with a ground-mass mainly glassy.

Less common is a '*microfelsitic*' or cryptocrystalline structure. This is seen in some of the dacites. In some cases spherulitic structures are found.

In most typical andesites, and especially in the pyroxene-bearing kinds, the ground-mass has the very distinctive 'felted' character termed by Rosenbusch *hyalopilitic*[2]. This consists of innumerable small felspar-laths, simple or once twinned, often with evident flow-structure, and a residuum of glassy matter. Vesicles are common, and their infilling by secondary products gives rise to amygdules[3]. So characteristic is this type, that it is often spoken of as the 'andesitic' ground-mass. When the little felspars are closely packed together, to the exclusion of any glassy base, we have the *pilotaxitic* structure of Rosenbusch. On the other hand, by

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[1] Koto, *Q. J. G. S.* (1884) xl, 441, 444.

[2] See chromolithograph of augite-andesite ('augite-porphyrite'), Berwerth, Lief. i.

[3] Very many of the amygdaloidal lavas (Ger. Mandelstein) belong here; Cohen (3), pl. lxxx, figs. 2–4.

increase in the proportion of isotropic base, these andesites graduate into more or less perfectly *glassy* forms. Wholly glassy types (andesite-obsidian, including andesite-pumice) are known in small development only, except in so far as they form part of tuffs, *etc.* Some andesitic rocks shew various kinds of *variolitic* structures[1] comparable with those seen in basalts (see fig. 44, *A*, on p. 198).

Leading types. Among *dacites* the best known are those of Tertiary age in Transylvania[2] and Hungary. They include holocrystalline examples (Kis Sebes, Rodna) and others with cryptocrystalline and microspherulitic ground-mass (Schemnitz district, *etc.*), as well as those having the hyalopilitic structure so common among the andesites. Hornblende-dacite with microspherulitic structure occurs among the recent lavas of Santorin in the Grecian Archi-pelago[3]. Zeolites and isotropic opal are found as secondary products, or in other cases chalcedony[4]. Fresh andesite-glasses also occur at Santorin[5], reproducing the perlitic fissures and other features of the acid obsidians. These seem to be in the main hornblende-bearing, but contain augite associated with that mineral. Vesicular and pumiceous modifications are found.

Among British Tertiary rocks the 'pitchstone' of the Sgùrr of Eigg[6] and the neighbouring islet Hysgeir[7] has apparently the composition of a dacite. The prominent phenocrysts are of sanidine, or perhaps anorthoclase, and are sometimes much corroded by the ground-mass. A little green augite and magnetite also occur. The ground is a brown glass rich in crystallitic growths or in minute felspar-microlites. Of older rocks, that described by Prof. Judd[8] from the (probably) Old Red Sandstone breccia near Scroggie-

[1] *G. M.* 1894, 551–553 (Carrock Fell dykes); Reed, *Q. J. G. S.* (1895) li, 183–187, pl. vi, figs. 6, 7 [2292, 2293] (Fishguard).

[2] The name was first used by Stache for quartz-bearing andesites in Transylvania (Dacia).

[3] Fouqué and Lévy, pl. xviii.   [4] *Ibid.* pl. xvii, fig. 2.

[5] *Ibid.* pl. xxx; xxxi, fig. 1.

[6] Judd, *Q. J. G. S.* (1890) xlvi, 380.

[7] *Q. J. G. S.* (1896) lii, 372.

[8] *Q. J. G. S.* (1886) xlii, 427–429, pl. xiii, figs. 7, 8.

side Farm in N.E. Fife is perhaps rather on the border-line between rhyolite and dacite. It has a glassy modification, which the author styles mica-dacite-glass. Phenocrysts of oligoclase and deep brown biotite are embedded in a glassy ground-mass containing trichites, globulites, and imperfect microlites of felspar (perhaps orthoclase). The glass shews beautiful perlitic fissures. Little is known of true dacites among the Lower Palæozoic lavas of this country, though some of the rocks included above as rhyolites would probably be styled dacites by certain petrologists. The name has also, as remarked above, been applied loosely to some of the acid intrusives.

A number of dacites were described from Nevada by Zirkel[1], and some of Richthofen's 'glassy rhyolites' from the same region seem to belong rather to this family[2]. Dacites are also well represented among the Tertiary and Recent lavas in California, Oregon, and Washington, and in San Salvador[3]. Biotite is prominent among the ferro-magnesian minerals, and sometimes hornblende. At Lassen's Peak in California[4] occurs a type rich in phenocrysts, which consist of plagioclase felspar, biotite, hornblende, and quartz, while the ground-mass is essentially of glass (fig. 41, A). This is one of the original 'nevadites,' and most of the rocks so styled are probably to be classed as dacites.

The andesites characterized by biotite or hornblende have affinities, as already remarked, with the typical trachytes. A *mica-andesite* free from hornblende is exceptional, but the name may be applied to varieties in which biotite is the dominant, though not the sole, ferro-magnesian constituent. The rocks usually taken as the type of *hornblende-andesite*[5] are those of the Tertiary volcanic district of the Siebengebirge, near Bonn, already alluded to as the home of certain typical

[1] *Micro. Petrogr. Fortieth Parallel* (1876), 134–142 : see also Iddings, *Monog.* xx *U. S. Geol. Sur.* (1893) 368–373 (Eureka district), and in Diller, 215–217.

[2] Hague and Iddings, *A. J. S.* (1884) xxvii, 460, 461.

[3] *Ibid.* (1886) xxxii, 29, 30.

[4] *Ibid.* (1883) xxvi, 231–233 ; Diller, 217–219.

[5] For coloured figures of several French examples see Fouqué and Lévy, pl. xxii, xxviii, xxix, xxxviii.

trachytes. In addition to abundant brown hornblende, these
andesites contain more or less biotite and a few prisms or
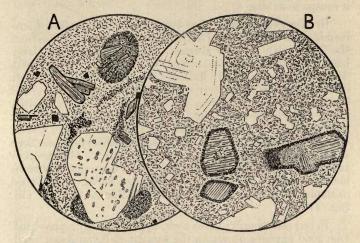
FIG. 41. ANDESITIC LAVAS, CALIFORNIA : ×22.

A. Dacite, Lassen's Peak. The phenocrysts are of andesine (some
with large glass-inclusions), hornblende, biotite, and magnetite. In
parts of the slide, not figured, quartz, sanidine, and pyroxene occur
more sparingly. The ground-mass is a clear glass crowded with little
acicular crystallites. There are also growths analogous to spherulites,
but with only very imperfectly radiate structure [2800].

B. Hornblende-Andesite, Mt Shasta. The phenocrysts are of horn-
blende (with resorption-border) and zoned labradorite. The ground-mass
consists of little microlites, chiefly of andesine [2802].

grains of pale green augite. The two former minerals always
shew the phenomenon of resorption. The Bolvershahn rock,
with a considerable amount of deep brown biotite, may be
called a hornblende-mica-andesite. The felspar phenocrysts
shew very marked zonary banding in polarized light. The
Wolkenburg rock is a characteristic hornblende-andesite. Its
phenocrysts include the three ferro-magnesian minerals men-
tioned, hornblende largely predominating, good crystals of
andesine, and a little magnetite and apatite, while its ground-

mass is of the trachytic type. A very similar rock is that of Stenzelberg, in which some of the hornblende crystals attain a conspicuous size.

In America Iddings[1] has recorded mica-andesites, hornblende-mica-andesites, and hornblende-pyroxene-andesites from the Tewan Mts in New Mexico. These rocks have a glassy base. Similar examples come from Lassen's Peak (Cal.), Mt Hood (Ore.), and Mt Rainier (Wash.)[2]. The phenocrysts often shew parallel intergrowths of hornblende, augite, and hypersthene. The 'trachytes' of Zirkel[3] and others in the Great Basin and elsewhere are in part hornblende-mica-andesites[4]. This type occurs with others at the Comstock Lode[5], and an example with beautifully zoned felspar phenocrysts has been described by Iddings[6] from the Eureka district. Others occur in the Sierra Nevada of California[7]. In these districts hornblende-andesites free from mica are also found, and a good example of this type comes from Mount Shasta, Cal. (fig. 41, *B*).

In our own country these rocks are very poorly represented. One good example occurs on the summit of Beinn Nevis[8], and, though probably of Carboniferous age, it is fairly fresh. The phenocrysts are of light-brown idiomorphic hornblende and a plagioclase full of glass-inclusions, *etc.* The ground-mass is obscured by specks of iron-ore and alteration-products, but is seen to consist largely of densely packed, minute felspar-microlites. Little is known of hornblende-andesites among the Lower Palæozoic and pre-Palæozoic lavas of Britain or of America. An Ordovician hornblende-andesite of somewhat basic composition occurs near Kildare[9], and others, brecciated

[1] *Bull. No.* 66 *U. S. Geol. Sur.* (1890) 12–16.
[2] Iddings, 12*th Ann. Rep. U. S. Geol. Sur.* (1892) 610–612, pl. LI : see also Diller, 221–223 (Mt Shasta, Cal.).
[3] *Micro. Petrogr. Fortieth Parallel* (1876), 143–162.
[4] Hague and Iddings, *A. J. S.* (1883) xxvi, 460.
[5] Hague and Iddings, *Bull. No.* 17 *U. S. Geol. Sur.* (1885) 23.
[6] *Monog.* xx *U. S. Geol. Sur.* (1893) 364–368, pl. v, figs. 1, 3, 4 ; vi, fig. 2 ; and in Diller, 219–221.
[7] Turner, 14*th Ann. Rep. U. S. Geol. Sur.* (1894) 487, 488.
[8] Teall, pl. xxxvii, fig. 1.
[9] Reynolds and Gardiner, *Q. J. G. S.* (1896) lii, 602.

and altered, are found on Slieve Gallion, co. Londonderry[1]. Good examples occur in Minnesota[2].

Andesites having a pyroxene as their dominant non-felspathic constituent are perhaps more widely distributed than any other group of lavas, and are largely represented among the products of volcanoes now active. Since a rhombic and a monoclinic pyroxene are often associated, the rocks are spoken of as *pyroxene-andesites*, while the marked predominance of one or other of these minerals gives a hypersthene- or an augite-andesite. Hypersthene-andesites, and hypersthene-augite-andesites in which the rhombic pyroxene predominates over the monoclinic, are especially widely distributed among the lavas of different periods. Prof. Judd[3] has pointed out that the same general petrographical type is found in lavas ranging in chemical composition from basalt to dacite. Thus the basic dykes of Santorin, the lava of Buffalo Peaks in Colorado, the Cheviot rocks, the recent lavas of Santorin, and the rocks of Krakatau consist of the same minerals in a glassy base of the same general composition, but the relative proportions of the minerals (in the aggregate basic) to glass (decidedly acid) varies in the different cases from 9 : 1 to 1 : 9. This illustrates the impossibility of naturally classifying by mineralogical characters alone rocks which have a glassy base.

The wide distribution of hypersthene-andesites in Europe and America was first insisted upon by Whitman Cross[4], who shewed that in a very large number of andesitic lavas hypersthene had previously been mistaken for augite. The rock upon which his first observations were made was from Buffalo Peaks, Colorado. The 'augite-andesites' of Zirkel[5] from Nevada have both rhombic and monoclinic pyroxenes, but

[1] Cole, *Sci. Tr. Roy. Dubl. Soc.* (1897) vi, 222, *etc.*

[2] Wadsworth, *Bull. No. 2 Geol. Sur. Minn.* (1887) pl. x, xi; Grant, 21*st Ann. Rep. Geol. Sur. Minn.* (1894) 57, 58.

[3] *G. M.* 1888, 1–11. For illustrations of the Krakatau rocks see *Rep. Krak. Comm. Roy. Soc.* (1888) pl. iii.

[4] *Bull. No.* 1 *U. S. Geol. Sur.* (1883); *A. J. S.* (1883) xxv, 139; and in Diller, 224–227.

[5] *Micro. Petrogr. Fortieth Parallel* (1876), 221–227, pl. xi, fig. 2.

the former predominates[1], and true augite-andesites seem to be unrepresented among the lavas of the Great Basin region. Hypersthene-andesites occur in great variety[2] among the Recent lavas of Mt Shasta (Cal.)[3], Mt Rainier (Wash.)[4], etc. These are crowded with phenocrysts of zoned plagioclase and pyroxenes, hypersthene predominating over augite, while the ground-mass varies from holocrystalline to vitreous. Andesites carrying hornblende in addition to hypersthene occur in the Eureka district[5], the Sierra Nevada[6], etc.

Pyroxene-andesites are abundant among the older volcanic rocks of Britain. Some in the Lake District contain plenty of pseudomorphs after a rhombic pyroxene (Falcon Crag near Keswick, etc.), while many others are characterized by monoclinic pyroxene only. A few of these rocks have been described by Mr Clifton Ward, Prof. Bonney, and Mr Hutchings[7]. The ground-mass is usually typically hyalopilitic.

In the Bala series of Caernarvonshire there are few andesites. Some, with augite only, occur in the Lleyn district[8], and one with dominant hypersthene forms an intrusive mass at Carn Boduan[9] in the same district. The andesites of the Stapeley Hills (Todleth, etc.) in Shropshire are of the same general type as the Cheviot rocks, containing both rhombic and monoclinic pyroxenes, and this is true also of the Bala lavas of the Breidden Hills (Moel-y-golfa, etc.)[10]. Pyroxene-andesites of Bala age are known at various localities in Ireland; e.g. Lambay Is.[11] and Portraine[12].

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[1] Cross, l.c.; Hague and Iddings, A. J. S. (1884) xxvii, 457–460.
[2] Hague and Iddings, A. J. S. (1883) xxvi, 222–235.
[3] Diller, 227, 228, pl. xxxii.
[4] G. O. Smith, 18th Ann. Rep. U. S. G. S. part ii (1898), 418–420.
[5] Iddings, Monog. xx U. S. Geol. Sur. (1893) 348–364, pl. vii, fig. 1.
[6] Turner, 14th Ann. Rep. U. S. Geol. Sur. (1894) 488; and 17th Ann. Rep. (1897) 617–619, pl. xlv, fig. A.
[7] G. M. 1891, 539–544.
[8] Bala Volc. Ser. Caern. 68.   [9] Ibid. 69–71.
[10] Watts, Q. J. G. S. (1885) xli, 539–543; Proc. Geol. Assoc. (1894) xiii, 337–339, with figures.
[11] Gardiner and Reynolds, Q. J. G. S. (1898) liv, 142–145.
[12] Ibid. (1897) liii, 521–527; Sollas, Pr. Geol. Ass. (1893) xiii, 100, with fig. 6,

Many of the old lavas loosely grouped under the field-term 'porphyrite' in the Old Red Sandstone and Carboniferous of Scotland are andesites, ranging in composition from a relatively acid type (dacite) to varieties verging on basalt. One of the former, from North-east Fife, has already been mentioned. In the same district are good examples of more basic types also (Northfield and Causeway Head)[1]. From Dumyat and elsewhere in the Ochils[2] come typical pyroxene-andesites with both hypersthene and augite, the former predominating. The freshest type has an unaltered glassy base, which in other varieties is devitrified. The Old Red Sandstone lavas of the Cheviots[3] are mostly hypersthene-andesites, containing both rhombic and monoclinic pyroxenes. The freshest type shews phenocrysts of labradorite, often honeycombed with inclusions of ground-mass, crystals of hypersthene shewing distinct pleochroism, and crystals and grains of pale augite, in a ground-mass of pale brown glass and felspar microlites (fig. 42). The ground sometimes has flow-structure, and shews varieties of the hyalopilitic type. The iron-ores are represented by magnetite and minute red scales of hæmatite. The rock is often veined by opal or chalcedony, stained red with ferric oxide. The more weathered lavas of the district (part of the 'porphyrites' of some authors) have had similar characters, but the felspars and pyroxenes are more or less decomposed, and the ground obscured by ferruginous matter. There are sometimes vesicles, filled with chalcedony, etc. Fresh examples come from Kilham, Longknowe, Haddan, and Coldsmouth Hills.

Certain dykes described by Mr Teall[4] in the North of England may be referred to here, being petrographically augite-andesites. Some of them (Cleveland, etc.) must be of Tertiary age, while others are possibly late Palæozoic. The

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[1] Judd, *Q. J. G. S.* (1886) xlii, 425–427, pl. xiii, figs. 1, 2.

[2] Flett, *Tr. Edin. G. S.* (1897) vii, 290–297, pl. xvii; Watts in Geikie's *Ancient Volcanoes* (1897), i, 274–276.

[3] Teall, pl. xxxvi, xxxvii, fig. 2; *G. M.* 1883, 102–106, 146–152, pl. iv, 252–254; Petersen, *G. M.* 1884, 226–234 (*Abstr.*); Watts, *Mem. Geol. Sur. Eng. and Wales, Expl. of Quarter-sheet* 110 *S. W., N. S. sheet* 3 (1895), 12, 13.

[4] *Q. J. G. S.* (1884) xl, 209–247, pl. xii, xiii; *Brit. Petr.* pl. xii, xiv.

Cleveland dyke is traced from near Whitby to Armathwaite near Carlisle, and perhaps farther. It contains porphyritic felspars, often broken, in a ground-mass composed of small

FIG. 42.   HYPERSTHENE-ANDESITE, CHEVIOT HILLS, NORTHUMBERLAND; × 20.

Phenocrysts of labradorite and hypersthene enclosed in a fine-textured ground-mass with a large proportion of glassy base [2762].

felspar crystals, minute crystals and grains of augite, crystals of magnetite, and abundant interstitial matter. This last is sometimes glassy, but commonly charged with various products of devitrification, giving a decided reaction with polarized light. The Acklington dyke is similar, but usually without the porphyritic crystals and with less of the interstitial base. The Tynemouth dyke is less fine-textured. It contains porphyritic aggregates of anorthite crystals in a ground-mass of elongated lath-shaped felspars, grains of augite, magnetite, and a considerable amount of interstitial base with devitrification-products and microlites and skeletons of felspar[1]. The dykes of Hebburn, Brunton (fig. 43), Seaton, and

[1] The structure is the 'intersertal' of Rosenbusch, who cites these dykes as examples of his 'tholeiite.'

Hartley are similar, though usually without the large felspars. Prof. Judd[1], who has described dykes of this type in Arran,

FIG. 43.   AUGITE-ANDESITE, BRUNTON DYKE, BINGFIELD,
NORTHUMBERLAND ; × 20.

The only minerals seen are felspar and augite.   There are, in addition, interstitial patches of brown glass, which enclose abundant crystallitic growths.   The structure is typically intersertal [2359].

remarks as characteristic of them the tendency of the glassy residue to become separated from the crystalline portion of the rock, either as a selvage, or as a central band, or in irregular patches and strings (Eskdalemuir in Dumfriesshire)[2], or, again, wholly or partially filling vesicles in the rock, as already remarked by Mr Teall[3] in the Tynemouth dyke. Different dykes belonging to this group vary much as regards the relative proportions of the crystalline elements and the glassy residue.   Specimens of various types may be found in Arran, the Cumbrae Isles, Skye, Donegal[4], etc.

[1] Q. J. G. S. (1893) xlix, 541.
[2] Geikie, Proc. Roy. Phys. Soc. Edin. (1880) v, 244–252, pl. v, vi ;
Teall, p. 196, pl. xxiv, fig. 1.
[3] G. M. (1889) 481–483, pl. xiv.
[4] Sollas, Sci. Pr. Roy. Dubl. Soc. (1893) viii, 91–93.

CHAPTER XIV.

BASALTS.

In the *basalt* family we include all the basic lavas except those in which a relatively high content of alkalies has given rise to the formation of minerals of the felspathoid group. The rocks range in texture from vitreous to holocrystalline. Except in a few of the latter (*dolerites*), the distinction between phenocrysts and ground-mass is commonly well marked, but the relative proportions of the two vary greatly in different types. The characteristic minerals in this family of rocks are a felspar rich in lime, augite, and olivine.

Following our principle, we shall make no distinction, as regards nomenclature and classification, between Tertiary and pre-Tertiary lavas. Foreign petrologists usually restrict the names basalt and dolerite to the newer examples, their older equivalents being denoted by such names as melaphyre, augite-porphyrite, diabase, *etc.*, some of which are also applied to rocks of the hypabyssal division.

Certain exceptional lavas (*limburgites, etc.*) which are of ultrabasic, rather than normally basic, composition will be briefly noticed. Some of them probably correspond rather with the nepheline-basalts, *etc.*, treated in the succeeding chapter.

Constituent minerals. The felspars of the basalts are of decidedly basic varieties. When distinctly porphyritic crystals occur, they seem to be usually *bytownite* or *anorthite*, while the felspars of the ground-mass are more commonly *labradorite.* The phenocrysts shew albite-lamellation, often

combined with pericline- and carlsbad-twinning. Zonary structure and zonary arrangement of glass-cavities are met with. The felspars of the ground-mass have the lath-shape, and are commonly too narrow to shew repeated twinning. Orthoclase is found only in certain abnormal types.

The dominant pyroxenic constituent is an ordinary *augite*, and this too may occur in two generations. If so, the phenocrysts often have good crystal-forms, with octagonal cross-section : twinning is frequently seen[1], and sometimes zoning and hour-glass structure. The colour is usually very pale, brownish or more rarely greenish, the latter especially in the interior of a crystal. The augite of the ground-mass is either in little idiomorphic prisms or in granules, and is often very abundant. Decomposition of the augite produces chloritic substances, *etc.*[2] A rhombic pyroxene, *hypersthene* or bronzite, occurs only in certain basalts, where it seems to some extent to take the place of olivine. It is always in idiomorphic prisms, and in the older rocks is very generally serpentinized. Some basalts, again, contain corroded crystals of *brown hornblende*, and others a little *brown mica*.

In the greater part of the basalts *olivine*[3] is an essential constituent, and in many it is abundant, though confined, as a rule, to phenocrysts. These are sometimes well shaped crystals, sometimes more or less rounded, while in some of the more glassy rocks hollow or skeleton crystals and crystallites occur[4]. The mineral is colourless or very pale green. It often shews serpentine-strings following cleavage- or other cracks[5], and with further alteration passes into various secondary products, serpentine, carbonates, *etc.* Another common change is the production of a red or brown margin to the olivine, due to iron-oxide, the olivine in basalts, and still more in limburgites, being often of a variety rich in iron[6]. Another mode of alteration sometimes met with results

[1] Cohen (3), pl. xxiv, fig. 3 ; xxv, fig. 1.
[2] Teall, pl. xxii, fig. 2.
[3] Cohen (3), pl. xlviii, fig. 2.
[4] *Ibid.* pl. i, fig. 3 ; xiv, fig. 2.
[5] Zirkel, *Micro. Petr. Fortieth Parall.*, pl. x, fig. 3 ; xi, fig. 3.
[6] Cohen (3), pl. lxi, fig. 1.

in the formation of brown pleochroic pseudomorphs of a mineral with a perfect cleavage and the appearance of a mica. It seems to agree in general characters with the mineral described in California by Lawson[1] under the name iddingsite; but the author named, regarding this as an original constituent, has made it the characteristic of a new group of lavas (carmeloites).

Octahedra and grains of *magnetite* are generally abundant, and this mineral frequently recurs in a second generation in little granules. Besides this, there are frequently little opaque or deep brown scales of *ilmenite* or deep red flakes of *hœmatite*. Grains of *native iron* occur locally in a few basalts (Ovifak in Disco, Greenland)[2].

Of other common minerals we need note only *apatite*, forming long needles, either colourless or of a faint violet or bluish tint.

A peculiar feature in certain American basalts[3] is the occurrence of isolated grains of *quartz*. These are always corroded by the magma and generally surrounded by a ring of augite or its alteration-products, a character usually associated with foreign quartz-grains picked up by a basic magma. In this case, however, there is reason to believe that the mineral is an original constituent formed under peculiar conditions. It is comparable with similar grains found in many lamprophyres (see above, p. 145).

Structures. The rocks of the basalt family present a wide range of characters, from purely glassy examples at one extreme to wholly crystalline at the other. Rocks exhibiting such a range may occur, perhaps exceptionally, in one district, their petrological characters being correlated with their various modes of occurrence, as is well described by Prof. Judd[4]. On the whole, the tendency to crystallization

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[1] *Bull. Geol. Dep. Univ. Cal.* (1893) i, 29-46, pl. IV.

[2] Fouqué and Lévy, pl. XXXVI, fig. 2; Steenstrup, *M.M.* i, 148, pl. VI.

[3] Diller, 252, 253, pl. XXVII; *A. J. S.* (1887) xxxiii, 45-49; *Bull. No.* 79 *U. S. Geol. Sur.* (1891) 24-29; Iddings, *A. J. S.* (1888) xxxvi, 209-213; *Bull. No.* 66 *U. S. Geol. Sur.* (1890) 16-31; *Monog.* xx. *U. S. Geol. Sur.* (1893) 393, pl. IV, fig. 1.

[4] *Q. J. G. S.* (1886) xlii, 66-82, pl. V, VI.

is much stronger here than in the more acid families of lavas. Again, the order of crystallization of the several constituents is less strongly marked, the mutual relations between augite and felspar, in respect of priority, varying, while the iron-ores, though they commonly begin to crystallize at an early stage, may be in part rather late. These remarks are true of both the 'intratelluric' and the 'effusive' periods, when these are distinctly separable; but in some of the holocrystalline types the porphyritic character is not recognizable. Some of these rocks differ in no essential from those already described as diabases, the petrological distinction between the hypabyssal and the volcanic types not being marked by any hard and fast line.

Except in the form of lapilli and fragments in tuffs, the purely vitreous type, *tachylyte*, is of very limited distribution, being found only as a very thin crust on some lava-flows or a narrow selvage to basalt-dykes. It consists of a brown or yellow glass densely charged with a separation of magnet-ite[1]. This is sometimes in globulites[2] disseminated through the glass so as to render it almost opaque, or collected in cloudy patches (cumulites); at other times it forms trichites or crystallites of minute size[3]. Perlitic structure is less common than in the obsidians. Interesting spherulitic struct-ures are met with in some examples[4]. When distinct pheno-crysts occur abundantly in the glassy ground-mass, we have what is sometimes called the 'vitrophyric' structure[5]. The basic glass is subject to secondary changes, probably involving, as a rule, hydration and other chemical changes; but the resulting substance, known as palagonite, is still an isotropic glass, yellow, brown, or sometimes green in sections.

Radiate aggregates of felspar microlites or fibres, answering to the spherulites of acid rocks, occur in some basaltic glasses, which are known as *variolites*. These aggregates vary in size and in the regularity of their structure, which ranges from

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[1] Cohen (3), pl. xxxix, figs. 1, 2.
[2] *Ibid.* pl. vi, fig. 4; iv, fig. 2.
[3] Judd and Cole, *Q. J. G. S.* (1883) xxxix, pl. xiv.
[4] Cole, *ibid.* (1888) xliv, 300–307, pl. xi.
[5] See chromolith., Berwerth, Lief. ii (Rhön).

mere fan-like and sheaf-like groupings (*cf.* fig. 44, *A*) to spherules with a perfect radiate structure. They may occur isolated in a glassy matrix, or coalesce into bands, or form a densely packed mass with little or no interstitial matter. The variolites are very susceptible to alteration.
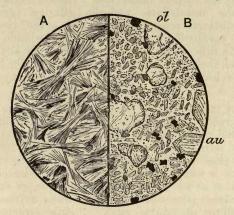
FIG. 44.

A. Andesite vein approaching the structure of variolite, Carrock Fell, Cumberland; ×20, crossed nicols. This is of the type which consists essentially of radiating felspar fibres grouped in sheaf-like bundles. There are also skeleton-prisms of a pyroxenic mineral, better seen in natural light [1552].   *B.* Limburgite, Whitelaw Hill, Haddington; ×20, natural light. Phenocrysts of olivine (*ol*), zoned augite (*au*), and magnetite are enclosed in a ground-mass of glass containing abundant prisms and granules of augite but no felspar. The glass, which constitutes the bulk of the ground, varies from brown to nearly colourless [1982].

Leaving the glassy basalts, we note those in which the ground-mass enclosing the phenocrysts of olivine, augite, felspar, *etc.*, is *hypocrystalline*, consisting of lath-shaped felspar-microlites and granules or microlites of augite with more or less of a residual glassy base. Of this division there are various types, depending on the relative proportions of augite, felspar, and glass, and the mutual relations of the minerals. When the felspar-microlites preponderate, usually with a

more or less fluxional arrangement, the ground-mass does not differ essentially from the 'hyalopilitic' type so common in the pyroxene-andesites.   Vesicles are frequent in such rocks. More often, however, augite is abundantly represented in the basaltic ground-mass.   Again, unindividualised glass may form the bulk of the ground, and this is especially the case in the limburgites (fig. 44, *B*).   Another type of structure, already noticed in the pyroxene-andesites, is the intersertal, in which a hypocrystalline or glassy ground-mass occurs only as angular patches in the interstices of the abundant phenocrysts (compare fig. 43).

By the failure of the glassy residue we pass to those types of basalt in which the phenocrysts are enclosed in a *holocrystalline* ground-mass.   Here again there are numerous
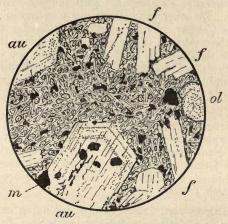
FIG. 45.   BASALT, ETNA LAVA OF 1669 ERUPTION, CATANIA;   ×20:

shewing phenocrysts of zoned augite (*au*), felspar (*f*), olivine (*ol*), and magnetite (*m*) in a holocrystalline ground-mass of little lath-shaped felspars and granules of augite and magnetite [131].

varieties.   Sometimes little eye-like or lenticular patches relatively rich in augite are contrasted with adjacent patches rich in felspar.   When felspar-microlites make up a large

part of the ground-mass, we have a structure analogous to the 'pilotaxitic' of some andesites and trachytes, the flow being more or less marked. On the other hand, the ground may consist mainly of small rounded granules of augite, between which the little felspars seem to be squeezed (fig. 45).

There remain the types distinguished as *dolerites* (usually olivine-dolerites), which, in the most typical examples, are holocrystalline rocks not conspicuously porphyritic, sometimes of coarse texture as compared with the generality of lavas. The chief structures are the granulitic and the ophitic, the distinction between which has been noticed under the diabases (p. 134). Typical ophitic structure is exceptional in most basaltic regions. Only rarely in doleritic lavas do we find an idiomorphic development of the augite.

Some dolerites enclose large scattered porphyritic crystals of felspar. In other cases there are porphyritic aggregates of crystals (felspar, olivine, augite, *etc.*) having the mutual relations characteristic of plutonic rocks : this is the *glomeroporphyritic* structure of Prof. Judd[1]. It is not confined to the holocrystalline dolerites. The crystals forming such a hypidiomorphic aggregate may still present idiomorphic outlines towards the surrounding rock[2].

Many Tertiary and Recent basalts in Germany, Auvergne, and other regions enclose so-called '*olivine-nodules*,' which are hypidiomorphic aggregates of olivine with enstatite, diopside, *etc.*[3] By some they have been regarded as very early intratelluric formations from the magma, by others as actual enclosed pieces of peridotites. Such nodules are not found in the British Tertiary basalts.

Leading types. Some basalts, belonging in general to the less basic varieties, are free, or nearly free, from olivine. These rocks usually carry a rhombic as well as a monoclinic pyroxene, and here, as in some other families, hypersthene may be considered as, to some extent, taking the place of the more basic silicate olivine. Such rocks, which may be

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[1] *Q. J. G. S.* (1886) xlii, 71, pl. vii, fig. 3.
[2] Teall, *ibid.* (1884) xl, 235, pl. xiii, fig. 1.
[3] Fouqué and Lévy, pl. xl, fig. 1.

styled *hypersthene-basalts*, occur among the Tertiary lavas of the western United States. Examples have been noted by Iddings[1] from the Eureka mining district in Nevada. The Ordovician lavas of the English Lake District are largely of this type, though, as already noticed, rhyolites and pyroxene-andesites are likewise found. Here the hypersthene is always converted into a light green, pleochroic, serpentinous substance comparable with bastite. The most striking variety, represented at Eycott Hill[2] and numerous other localities in the district and at Melmerby[3] near Cross Fell, has large rounded
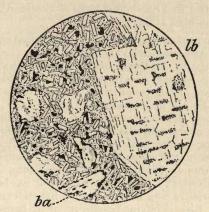
Fig. 46. Hypersthene-basalt, Eycott Hill group, Melmerby, Cumberland; ×20.

To the right is one of the large crystals of labradorite (*lb*) with its peculiar inclusions. The hypersthene is represented by bastite pseudomorphs (*ba*): augite occurs in less abundance. These, with the little felspar-prisms, the granules of magnetite, and some residual glassy base, make up the bulk of the rock [1251].

phenocrysts of labradorite with carlsbad and albite-twinning. These contain rather large opaque inclusions in the form of

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[1] *Monog.* xx *U. S. Geol. Sur.* (1893) 386–394, pl. vii, fig. 2.
[2] Ward, *Monthly Micro. Journ.* (1877) xvii, 240–245; Bonney, *G. M.* 1885, 76–80; Teall, 225–227.
[3] *Q. J. G. S.* (1891) xlvii, 517.

negative crystals and smaller enclosures with zonary disposition. In other varieties of the lavas these large crystals are not present. The ground-mass consists of slender striated prisms of plagioclase, crystals of hypersthene converted to pleochroic bastite, granules of augite, abundant magnetite, and an isotropic base (fig. 46). In the basic lavas of the Lake District olivine is entirely wanting. Hypersthene, pseudomorphed by bastite, is frequently present, but rarely to the exclusion of augite.

Basalts devoid of olivine seem to be widely distributed among the Old Red Sandstone lavas of Scotland[1], where some of them have been styled porphyrites.

We come next to the more widely distributed *olivine-basalts*. Such rocks are extensively developed among the lavas of late geological age in America; for instance, in the Great Basin region, lying between the Rocky Mts and the Sierra Nevada. Here they are mostly porphyritic, with relatively large phenocrysts of olivine, plagioclase, and occasionally augite, in a glassy, microlitic, or microcrystalline ground-mass. A smaller number are non-porphyritic, consisting of a uniform aggregate of plagioclase, augite, olivine, and magnetite, often with a considerable amount of glassy base[2]. Other examples have been described from the Sierra Nevada[3], the Tewan Mts (N.M.)[4], and San Salvador[5]. In the latter region it has been remarked that the varieties poor in olivine carry hypersthene in addition to augite. Recent olivine-basalts occur at many localities in Colorado, New Mexico, Arizona, and about Mt Shasta and Lassen's Peak in California.

The Tertiary basaltic rocks of Britain, as developed in the Inner Hebrides and in various parts of the west of Scotland and the north of Ireland, are in great part olivine-basalts.

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[1] Peach and Horne, *Tr. Roy. Soc. Edin.* (1884) xxxii, 379, 380; pl. xlv, figs. 1, 2 (Shetland).

[2] Hague and Iddings, *A. J. S.* (1884) xxvii, 456, 457; *cf.* Zirkel, *Micro. Petr. Fortieth Parallel* (1876), 229–254; pl. x, figs. 1, 3, 4; xi, fig. 3.

[3] Turner, *14th Ann. Rep. U. S. Geol. Sur.* (1894) 490–492.

[4] Iddings, *Bull. No. 66 U. S. Geol. Sur.* (1890) 16.

[5] Hague and Iddings, *A. J. S.* (1886) xxxii, 27, 28.

They have been well described by Prof. Judd[1], who considers that the varied series of structures which they present constitute intermediate types between the holocrystalline plutonic rocks at the one extreme and the glassy basalts (tachylytes) at the other. He distinguishes two parallel lines of transition. One, characteristic of the true extruded lava-flows, includes the 'granulitic' dolerites and the basalts in which the augite tends to form granules between the felspar prisms ('microgranulitic' structure). The other series of varieties includes the ophitic dolerites and the micro-ophitic basalts, in which the augite tends to enwrap and enclose the felspars : this seems to be the case especially in intrusive members of the group. The distinction is traceable even in those basalts which consist largely of a glassy base, the crystallitic growths enclosed in the glass being in the one case in the form of granules and short microlites, often rounded, in the other case in the form of skeleton-crystals and more spreading growths. In the true lava-flows both granulitic and ophitic varieties are found, but the former are the more common. Varieties with much glassy base are not of frequent occurrence. An amygdaloidal structure is very general, and the most common contents of the amygdules are minerals of the zeolite group.

Some of the Scottish Tertiary dolerites and basalts are porphyritic, the felspar occurring in two generations, of which the earlier is a thoroughly basic variety, sometimes near anorthite, while the latter is less basic, usually labradorite. Porphyritic augite, however, is not found, and this feature distinguishes the group of rocks in question from the Tertiary basalts of various European areas and also from many Carboniferous basalts of Scotland and Ireland. The corresponding rocks of the Antrim plateau present like features. As described by Prof. Watts[2], some of the basalts have porphyritic felspars, but most are of quite compact character. Olivine grains are enclosed in a mass of elongated felspar-crystals and granules of augite, with occasionally a second generation of smaller olivines.

[1] Q. J. G. S. (1886) xlii, 49–95, pl. iv–vii ; see Teall, pl. x.
[2] Guide, 79.

The basic lavas of Carboniferous age in this country are also characteristically olivine-bearing rocks. Those of Derbyshire (to be distinguished from the ophitic olivine-diabases of intrusive habit) are porphyritic olivine-basalts with olivine and large augite phenocrysts in a ground-mass of small felspar laths, augite grains and prisms, and iron-ores, with little interstitial matter (Blackwell Lane, Great Low)[1].

The Kelso lavas, in the Lower Carboniferous of the Cheviot district, are olivine-basalts with phenocrysts of anorthite. One from Stichill in Roxburghshire was described by Mr Teall[2]. In other examples, from Northumberland, Prof. Watts[3] notes brown pleochroic pseudomorphs after olivine, which he identifies with iddingsite.

The Carboniferous olivine-basalts of the southern half of Scotland present a considerable variety of characters[4]. The commonest type has rather abundant small olivines and grains of augite in a mesh of slender felspars with microlitic augite and minute granules of magnetite (Dalmeny, Bathgate Hills, etc.). In another type the olivine phenocrysts are large, and the felspar microlites are found only in small amount (lowest lavas of Bathgate Hills, Linlithgowshire). A well-known rock from the Lion's Haunch on Arthur's Seat, Edinburgh[5], has numerous large, well-built crystals of augite, olivine, and felspar, with small crystals of magnetite, in a ground-mass of little crystals and microlites of felspar, granules of augite and magnetite, and some residual glass. In the lava of Craiglockhart Hill the ground-mass is more glassy, while the phenocrysts are augite and olivine without felspar. On the other hand, there is a holocrystalline type, which is an olivine-dolerite with granulitic to sub-ophitic structure (Gallaston, N.W. of Kirkcaldy). A curious variety, very rich in felspar,

[1] Arnold-Bemrose, *Q. J. G. S.* (1894) l, 624; *Pr. Geol. Ass.* (1899) xvi, 213, 214.

[2] *G. M.* (1883) 258–260, pl. vi.

[3] *Mem. Geol. Sur. Engl. and Wales, Expl. Quarter-sheet* 110, S. W., N. S. sheet 3 (1895), 14.

[4] Geikie, *Q. J. G. S.* (1892) xlviii, *Proc.* 105, 106; Watts in Geikie's *Ancient Volcanoes* (1897), i, 418, and *Ann. Rep. Geol. Sur.* for 1896, 64, 65.

[5] Teall, pl. xxiii, fig. 1.

comes from Markle quarry in the Garlton Hills, Haddington-shire[1]. Here olivine occurs only in small sporadic grains, while phenocrysts of labradorite are numerous, and the ground-mass consists of laths, microlites, and granules of felspar with dispersed magnetite and probably only a little augite.

A rock very like that of Lion's Haunch occurs as a dyke near the Stack of Scarlet in the south of the Isle of Man[2]. The phenocrysts are large idiomorphic crystals of fresh plagio-clase and violet-brown augite, with pseudomorphs of calcite and serpentine after olivine. The ground-mass is of lath-shaped felspars, augite, and iron-ores. This is probably con-nected with the Carboniferous volcanic series of the Stack, which consists of tuffs with dykes and probably flows of a more compact basalt[3]. The latter is considerably decomposed, the augite being converted into chloritic and other products. Porphyritic felspars occur, and the little lath-shaped felspars of the ground-mass shew a fluxional arrangement. The much fresher basalt, which forms numerous small dykes in the south of the Isle of Man[4], is probably of Tertiary age.

In the neighbourhood of Limerick is a considerable de-velopment of basaltic lavas of Carboniferous age. These differ from the Irish Tertiary basalts in various points, and especially in the frequent presence of augite among the phenocrysts.

Olivine-basalts do not figure largely in the great volcanic groups which characterize the Lower Palæozoic in various parts of Britain. Sir A. Geikie[5] has noted olivine-basalts of early Cambrian (or late pre-Cambrian) age near St David's (Rhosson, Clegyr Foig, etc.). The idiomorphic crystals of olivine in these rocks are replaced largely by hæmatite. The ground-mass consists of augite-granules, abundant octahedra of magnetite, and a base crowded with globulites and trichites, felspar being only occasionally recognized. These characters suggest a resemblance to the limburgite type, noticed below.

[1] Hatch, *Trans. Roy. Soc. Edin.* (1892) xxxvii, 119, pl. i, fig. 2.
[2] Hobson, *Q. J. G. S.* (1891) xlvii, 443, 444.
[3] *Ibid.* 441.　　　　[4] *Ibid.* 445–447.
[5] *Q. J. G. S.* (1883) xxxix, 304, pl. ix, fig. 4. On basalts from Skomer Is. see Howard and Small, *Tr. Cardiff Nat. Soc.* (1897) xxviii, part i, with plate.

In America ancient olivine-basalts have been described from Nôtre Dame Bay in Newfoundland[1], North Haven in Maine[2], South Mountain in Pennsylvania[3], the Penokee (Huronian) group[4], Keweenaw Point, *etc.* (Mich.), and other localities in the Lake Superior region[5], the Grand Cañon of the Colorado[6], and other districts of pre-Cambrian and Lower Palæozoic rocks.

The name *tachylyte* is commonly employed to cover the glassy representatives of both the basalts and the pyroxene-andesites. Examples occur at numerous places in the Tertiary volcanic districts of Skye, Raasay, and Mull[7], and in Co. Down (Slievenalargy)[8]. All these are thin selvages of dykes and sills, the most considerable development of basic glass in Britain being at a locality near Loch Scridain in Mull[9]. The rocks usually enclose small crystals of magnetite and sometimes of olivine, augite, and felspar. The glass is crowded with incipient growths of magnetite and occasionally of other minerals. These take the form of globulites, sometimes collected into cumulites (the Beal in Skye), of margarites (Lamlash near Arran), or of numerous minute opaque rods (Sorne in Mull, *etc.*), sometimes accompanied by transparent crystallites and belonites (Gribun in Mull). Spherulites occur in some instances. In the tachylyte of Ardtun in Mull[10] they are sometimes isolated, sometimes in bands, sometimes packed together, with polygonal boundaries to the exclusion of any glassy matrix. When imperfect, they seem to consist of brown globulitic matter, which is more condensed towards the centres. When better developed, they shew radiating fibres

[1] Wadsworth, *A. J. S.* (1884) xxviii, 95.

[2] G. O. Smith, *Joh. Hopk. Univ. Circ.* No. 121 (1895).

[3] G. H. Williams, *A. J. S.* (1892) xliv, 490–492.

[4] Van Hise, *Monog.* xix *U. S. Geol. Sur.* (1892) 410.

[5] Pumpelly (Irving), *Copper-bearing Rocks, etc., Monog.* v *U. S. Geol. Sur.* (1884) 69–77, pl. ix.

[6] Iddings, *14th Ann. Rep. U. S. Geol. Sur.* (1894) 520–524.

[7] Judd and Cole, *Q. J. G. S.* (1883) xxxix, 444–462, pl. xiii, xiv. For localities of numerous other examples in Mull, see Kendall, *G. M.* 1888, 555–560.

[8] Rutley, *Journ. Roy. Geol. Soc. Ire.* (1877) iv, 227–232, pl. xiv.

[9] Heddle, *Tr. G. S. Glasg.* (1895) x, 81–85.

[10] Cole, *Q. J. G. S.* (1888) xliv, 300–307, pl. xi.

arranged in sectors, some brown and others grey, with pleochroism in both cases. But little is known of tachylytes among the older volcanic rocks[1].

Closely allied to the spherulitic tachylytes are the rocks known as *variolite*, of which examples have been described from Anglesey, the Lleyn district of Caernarvonshire, and various parts of Ireland[2]. The spherules shew considerable variety of structure, ranging from mere fan-like groupings of felspar microlites (*cf.* fig. 44 *A*) or sheaf-like aggregates with a lath-shaped crystal as nucleus (see Sollas) to very regular, radiate, spherulitic growths. They may be closely packed to make up the entire mass of a portion of the rock, or arranged in bands, or isolated in a matrix of brown or greenish glass with cumulites, globulites, *etc.* (see Cole). The individual spherules are commonly from one-tenth to one-half of an inch in diameter, but sometimes less or more. Secondary changes may cause devitrification of any glassy matrix, and give rise to a separation of iron-oxides, a production of epidote, *etc.* An example remarkable alike for the large scale of its structure and the perfection of its preservation comes from Camas Daraich at the southern extremity of Skye[3]. Here the spherules, sometimes as much as 2 or 3 inches in diameter, are built of radiating felspar fibres with minute skeleton crystals of olivine and granules of augite, while in one variety of the rock there is a considerable amount of interstitial glassy base. Variolite is found sometimes in small dykes, sometimes as a margin to larger basic intrusions or lava-flows, sometimes again in the interior of a diabase-mass, either bordering spheroidal joints or forming a selvage on irregular pillow-like portions into which the rock-mass is divided[4].

[1] See Groom, *Q. J. G. S.* (1889) xlv, 298–304, pl. xii (Carrock Fell).
[2] Miss Raisin (Lleyn), *Q. J. G. S.* (1893) xlix, 145–159, pl. i ; Cole (Careg Gwladys, Anglesey), *Sci. Proc. Roy. Dubl. Soc.* (1891) vii, 112–120, pl. x ; (Annalong, Co. Down) *ibid.* (1892) 511–519, pl. xxi ; (Dunmore Head, Co. Down) *ibid.* (1894) viii, 220–222 ; Sollas (Roundwood, Co. Wicklow) *ibid.* (1893) 99–106, figures. For coloured figure of the 'variolite of the Durance' see Fouqué and Lévy, pl. xxiv, fig. 2.
[3] Clough and Harker, *Tr. Edin. G. S.* (1899) vii, 381–389, pl. xxiii.
[4] On this and other points see Cole and Gregory (M. Genèvre), *Q. J. G. S.* (1890) xlvi, 295–332, pl. xiii ; Gregory (Fichtelgebirge), *ibid.* (1891) xlvii, 45–62.

Certain lavas of very restricted distribution verge on the ultrabasic in composition[1]. Here belong the *limburgites* of Rosenbusch (magma-basalts of Bořicky), lavas of highly basic nature, rich in olivine and augite and devoid of felspar. The best British examples yet recorded are from the Carboniferous of Scotland and Ireland. Dr Hatch[2] has described one from Whitelaw Hill, near Haddington, which is in a very fresh condition. There are abundant well-shaped phenocrysts of olivine and augite, the latter having a very pale violet-brown tint in the interior, deepening towards the margin, with slight pleochroism. These minerals, with imperfect crystals of magnetite, occur in a ground-mass consisting of small augite-prisms set in brown to pale yellowish or colourless glass (fig. 44, *B*). Prof. Watts[3] has noted a limburgite in the Limerick district (Nicker), which closely resembles the preceding, though less perfectly preserved, the olivine being replaced by carbonates, *etc.* The augite has a strong zonary structure, the violet-brown tint being noticeable, while the interior of each crystal is paler or has a greenish colour. Augite in a second generation, magnetite granules, and more or less altered glass make up the ground-mass. Similar lavas occur at Phillipstown is Queen's County[4], and Prof. Watts has also detected a limburgite among the probably Tertiary volcanic rocks of Scalnagowan in Clare. These British examples are sufficiently like the typical rocks of Limburg[5], near the Kaiserstuhl, *etc.*, to render detailed description of these unnecessary. They are characteristically very basic lavas, in which crystallization has been arrested, both in the 'intratelluric' and in the 'effusive' period, before the separation of felspar had begun. The olivine is often a variety rich in iron, and becomes converted at the margin of the crystal into deep red hæmatite or brown limonite[6].

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[1] Prof. Bonney remarks that chemically the limburgites occupy a transitional position between the olivine-dolerites and the picrites: *G. M.* 1901, 411–417.

[2] *Trans. Roy. Soc. Edin.* (1892) xxxvii, 116, 117, pl. I, fig. 1.

[3] *Rep. Brit. Ass.* for 1892, 727.

[4] Watts, *Guide*, 38, 94.

[5] Cohen (3), pl. xxiii, fig. 3; xxv, fig. 1; lxi, fig. 1.

[6] Fouqué and Lévy, pl. lii, fig. 2.

The *hornblende-basalts*, in which brown hornblende occurs as phenocrysts, are a peculiar group, of thoroughly basic composition. Examples occur in the Rhön district and the Westerwald, in Madagascar[1], *etc.* Basalts in which hornblende is a prominent ferro-magnesian constituent are, however, not unknown in the Carboniferous of Britain (Elie in Fife).

A peculiar group of basic lavas rich in alkali may be termed *orthoclase-basalts*, this mineral figuring largely in the ground-mass of the rocks. They have been described by Iddings[2] as dykes and flows occurring at numerous places in the Yellowstone Park district. The most basic varieties (Absaroka type) have phenocrysts of olivine and augite ; in the Shoshone type labradorite comes in in addition ; and in the Banak type, including the most acid of the rocks, this mineral preponderates. Here too the rocks become more felspathic, and biotite largely replaces augite. Rocks corresponding with the Absaroka type occur in the Bozeman district, Montana[3]. Although mentioned in this place, these alkali-basalts recall by their remarkable association of minerals certain rocks (ciminites) which we have considered as basic trachytes.

[1] Hatch, *Q. J. G. S.* (1889) xlv, 349–352.
[2] *Journ. Geol.* (1895) iii, 935–959.
[3] Merrill, *Proc. U. S. Nat. Mus.* (1895) xvii, 638–641, 665–671.

CHAPTER XV.

LEUCITE- AND NEPHELINE-BASALTS, ETC.

WE shall group together for convenience various basic and ultrabasic lavas in which leucite, nepheline, or, in certain types, melilite is a prominent constituent, with or without a lime-soda-felspar. In the phonolites and leucitophyres, described above, a potash-felspar was an essential mineral, and the rocks had other affinities with the trachytes. Although some of the rocks to be noticed resemble the phonolites and leucitophyres in some features, they are for the most part allied rather with the basalts, while the varieties having any considerable amount of glassy base graduate into the limburgites and augitites[1].

The rocks in which leucite or nepheline only partly takes the place of felspar are termed *leucite*- or *nepheline-tephrites* when free from olivine, and *leucite*- or *nepheline-basanites* when containing that mineral. For those rocks which have the felspathoid minerals to the exclusion of felspar the name *leucitite* or *nephelinite* is used when olivine is absent, and *leucite*- or *nepheline-basalt* when olivine is present. In all these divisions the leucite-bearing and the nepheline-bearing types are on the whole distinct, though the rocks characterized by either of the minerals may contain the other as an accessory.

To these types may be added the *melilite-basalts*, in which the mineral named is abundant, usually with little or no

[1] See, *e.g.*, G. H. Williams, *A. J. S.* (1889) xxxvii, 188 (Fernando de Noronha).

felspar and with abundant olivine. Rosenbusch separates from the lavas, under the name alnöite, a rock which occurs in dykes in association with nepheline-syenite, and has affinities with some of the lamprophyres.

The rocks here noticed are known chiefly from districts of Tertiary and Recent volcanic rocks. A few examples of Palæozoic age have, however, been recorded: leucite-tephrite from the Maconnais, leucitite from Siberia, melilite-basalt from Canada, *etc.*

Constituent minerals. The *leucite* of these rocks may be in two generations, differing in size. The crystals are always idiomorphic icositetrahedra, but often more or less rounded. They usually shew feeble birefringence and the characteristic lamellar twinning[1]. Augite microlites and granules, glass-inclusions, *etc.*, are often arranged in zones, or grouped in the centre of the crystal[2].

The *nepheline* in the porphyritic types is usually confined to the ground-mass. In the nephelinites and nepheline-basalts it is commonly idiomorphic, except in some of the holocrystalline rocks. In other types it often forms small allotriomorphic crystals, not easily identified, and its distribution may be local. It can sometimes be made evident by staining with fuchsine. The common alteration-products are natrolite and other soda-zeolites in radiating aggregates.

Other felspathoid minerals, *sodalite, haüyne*[3], and *nosean*, are not uncommon as phenocrysts in the rock-types richest in leucite and nepheline, but they occur only as accessories.

The yellow or colourless *melilite*[4] is recognized by its weak double refraction, straight extinction, and peculiar microstructure. Idiomorphic crystals have a tabular habit parallel to the base, and the basal faces sometimes form concave curves. The mineral may also be quite allotriomorphic, and, when it occurs as an accessory in leucite-lavas, has sometimes the

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[1] Cohen (3), pl. xxviii, fig. 3.
[2] *Ibid.* pl. vii, fig. 1; xiv, fig. 1; xvii, fig. 2; xix, fig. 1.
[3] *Ibid.* pl. xxi, fig. 3.
[4] For good figures see Stelzner, *Neu. Jahrb., Beil.* Bd. ii (1882), pl. viii.

form of a framework enclosing other minerals in poecilitic fashion (fig. 48).

This latter mode of occurrence is sometimes seen also in the *sanidine* which occurs as an accessory in some of the leucite- and nepheline-lavas, linking them with the leucito-phyres and phonolites. The *plagioclase* felspars, which are found in some types of these rocks, are always of a basic variety. There may be phenocrysts with idiomorphic outline, tabular habit, albite-lamellation, zonary structure, and zones of glass-inclusions; while the felspars of the ground-mass vary from narrow laths, often only once twinned, to mere microlites. These shew a tendency to spherulitic arrangement, and the phenocrysts too may form radially grouped aggregates (fig. 47).

The usual coloured constituent in the rocks here considered is *augite*. It often occurs in two generations, the earlier relatively large and well shaped[1]. The colour is commonly green, but often varies in concentric zones[2], becoming sometimes pale violet, with distinct pleochroism, at the margin of a crystal. Again, there are sometimes two kinds of porphyritic augite, differently coloured. Some nephelinites have a purple-brown, pleochroic, 'hour-glass' augite. Exceptionally some of the rocks contain little yellowish-green needles of *ægirine*. A brown or red-brown or red *biotite* is very common in the nepheline- and melilite-rocks, often shewing resorption-phenomena. Brown *hornblende* is an occasional accessory in some rocks, and commonly shews a corrosion-border of magnetite and augite[3].

Olivine is an essential constituent in many of the types, and has the same general characters as in basalts. In some of the most basic rocks the mineral is a hyalosiderite, and often becomes red by the separation of iron-oxide.

Iron-ores are commonly present, and in the olivine-bearing rocks often abundant. They are *magnetite* and *ilmenite*, the latter sometimes in deep brown translucent scales.

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[1] Cohen (3), pl. XLII, figs. 1, 2.
[2] *Ibid.* pl. II, fig. 4; XVIII, fig. 4.
[3] *Ibid.* pl. IV, fig. 4.

Apatite is a pretty constant accessory, usually in little prisms with the characteristic cross-jointing[1], though in some of the nepheline-dolerites, *etc.*, it builds larger and stouter crystals. A pale violet or blue tint, with evident dichroism, is not infrequent. Some of the leucite- and nepheline-lavas have *melanite*-garnet, brown in slices and always isotropic. A very common accessory in the melilite-basalts and some nepheline-rocks is *perofskite* in minute octahedra, shewing in high relief in consequence of their refractive index[2].

Leading types. Our illustrations must be drawn almost entirely from foreign sources, since, with the exception of the few phonolites already noted, lavas containing felspathoid minerals are not found within the British area.

It must be noticed that the several types to be distinguished are not always sharply marked off from one another. This is especially the case with the felspar-bearing members, the tephrites and the basanites having in great measure the same general characteristics, except for the not very considerable proportion of olivine in the latter. The differences between the leucitites and nephelinites on the one hand and the leucite- and nepheline-basalts on the other are, however, more marked, the olivine-bearing types being notably richer in the ferro-magnesian constituent (augite) and in iron-ores. Among rocks characterized specially by melilite, the only important type is melilite-basalt, containing abundant olivine and typically no felspar.

A well-known *leucite-tephrite* comes from Tavolato[3] near Rome. It is remarkable for an abundance of blue haüyne. There are two generations of leucite, both shewing twin-lamellation. A greenish-brown ægirine occurs as well as augite. Both lath-shaped plagioclase and sanidine are found, the latter sometimes occurring as an interstitial matrix to the other minerals, though in other examples there is some glassy residue. The rock also contains grains of melanite. Other

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[1] Cohen (3), pl. xlvii, fig. 1.
[2] *Ibid.* pl. iii, fig. 1.
[3] *Ibid.* pl. xxvii, fig. 2.

Italian examples have been described[1], and leucite-tephrites have also been described from the Kaiserstuhl (near Freiburg in the Breisgau), from Bohemia, *etc.* The Bohemian rocks contain no haüyne, and have leucite confined chiefly to the holocrystalline ground-mass.

The lavas of Vesuvius[2] stand between leucite-tephrite and *leucite-basanite*, olivine being, as a rule, not very abundant. The conspicuous phenocrysts are of leucite (with inclusions of brown glass and augite-microlites), plagioclase (often in radiating groups of crystals), augite, and usually olivine (fig. 47), and the same minerals, except the last, recur as constituents of the ground-mass. Magnetite and apatite are always present, and in some cases biotite is plentiful. Nepheline, sanidine, and brown hornblende are rarer, and sodalite is confined to crevices, where it seems to have been formed after the consolidation of the rock. The ground-mass is usually holocrystalline or with only a little brownish or yellowish glass, but there are vitreous[3] and pumiceous modifications. The lavas of Vulcanello, as described by Bäckström, represent a different variety, also poor in olivine. Leucite is confined to the ground-mass, and part of the felspar in the ground is of a potash-bearing species.

The rock described by Hague[4] from the Absaroka range in Wyoming resembles a leucite-basanite, but has affinities with the leucitophyres. Olivine and augite are porphyritic in a ground-mass essentially of leucite and sanidine, plagioclase being only scantily represented. Magnetite, apatite, and a little mica are present, and there may be a very small proportion of glassy base.

The scoriaceous lava of Niedermendig, in the Laacher See district, which has been largely employed for mill-stones[5], is

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[1] Washington, *Journ. Geol.* (1896) iv, 561–564 (Bolsena); *ibid.* (1897) v, 42, 43 (L. Bracciano), and 246–248 (Rocca Monfina).

[2] Cohen (3), pl. ii, fig. 4; xiv, fig. 1; xvii, fig. 2; xix, fig. 1; xxxix. fig. 4; Fouqué and Lévy, pl. xlix, fig. 1; Haughton and Hull, *Tr. Roy. Ir. Acad.* (1875) xxvi, pl. ii.

[3] Fouqué and Lévy, pl. xli, fig. 2; Cohen (3), pl. iii, fig. 2.

[4] *A. J. S.* (1889) xxxviii, 45. This rock falls under the leucite-absarokite of Iddings, *Journ. Geol.* (1895) iii, 939.

[5] *Cf.* Clements, *Bull. No. 5 Geol. Sur. Ala.* (1896) 142, 143.

placed between leucite- and nepheline-tephrite. Its conspicuous crystals of haüyne are regarded by Lehmann as of foreign derivation. The so-called haüynophyre of Mte Vulture, near Melfi, has both leucite and nepheline in its ground-mass, while the most abundant phenocrysts are of blue haüyne and yellow augite.
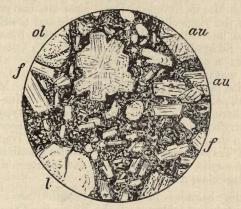
FIG. 47. LEUCITE-BASANITE, VESUVIUS; × 20.

This shews leucite (*l*) and crystals or groups of felspar (*f*), both with zones of inclusions, augite (*au*), olivine (*ol*), magnetite, and a little isotropic residue [845].

The lavas of the Canary Islands afford a great variety of *nepheline-tephrites*[1] and nepheline-basanites, the former predominating. Some of them are of the so-called 'basaltoid' type, in which nepheline is not present in any large proportion. The structure is usually holocrystalline. The 'phonolitoid' type is richer in nepheline, and sometimes has blue or yellow haüyne. Here hornblende is found in varying proportion, sphene occurs, and a predominance of sanidine over plagioclase in some varieties indicates affinity with the phonolites.

[1] Cohen (3), pl. IV, fig. 4; XVI, fig. 3; LXVI, figs. 3, 4.

Hornblende-bearing nepheline-tephrites occur also in the Rhön (to the north of Bavaria), in the Thüringer Wald, *etc.* There are also rocks, named 'basanitoid' by Bücking, having no actual nepheline, but a glassy base very rich in soda to represent that mineral.

Nepheline-tephrites have been described by Zirkel[1] from the Kawsoh Mts in Nevada. These have sanidine predominating over the plagioclase: augite crystals and needles, magnetite, and interstitial nepheline are the other constituents. From the Elkhead Mts and other localities in Colorado the same writer[2] notes examples of *nepheline-basanite.* One type, of coarse texture, has large crystals of olivine, idiomorphic zoned augite, plagioclase, and interstitial nepheline. Magnetite is plentiful, and biotite is often present. A nepheline-basanite from Southern Texas[3], on the other hand, is of a type poor in olivine, carrying brown hornblende among the phenocrysts and sanidine in the ground-mass. From the western (Trans-Pecos) district of Texas comes a nepheline-tephrite containing abundant green augite, brown hornblende, and biotite in a groundmass of plagioclase and nepheline[4].

Nepheline-basanites in considerable variety are associated with the nepheline-tephrites of the Rhön, the Canaries, *etc.* Some are poor in nepheline and felspar, and approximate to the limburgites. Doelter's 'pyroxenite' (augitite) from the Cape Verde Islands is similar, having only crystals of augite and some magnetite in a glassy ground-mass of composition agreeing with nepheline.

Good examples of the type *leucitite* come from the Alban Hills, near Rome (Capo di Bove[5], *etc.*). They are nonporphyritic rocks, very rich in leucite and relatively poor in augite. Other constituents are brown biotite, yellow striated melilite, and clear sanidine, all of which occur in crystal-plates

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[1] *Micro. Petrogr. Fortieth Parallel* (1876), 255, 256.
[2] *Ibid.* 256–258.
[3] Osann, *Journ. Geol.* (1893) i, 344–346.
[4] Osann, *4th Ann. Rep. Geol. Sur. Tex.* (1892) 134.
[5] Cohen (3), pl. ii, fig. 2, and pl. xxviii, fig. 3; Fouqué and Lévy, pl. l, fig. 1. See also fig. 2 of latter for a type richer in augite, from Frascati.

enclosing the leucite and augite in pœcilitic or ophitic fashion (fig. 48). Other leucitites come from neighbouring volcanic districts[1].
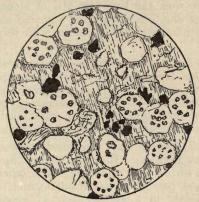
FIG. 48. LEUCITITE, CAPO DI BOVE, NEAR ROME; ×100.
Small leucites with zonally grouped inclusions are numerous, and augite and magnetite also occur. All these are enclosed by a large crystal of yellowish striated melilite. In other parts of the slide sanidine plays a similar part [G 243].

The rock described by Zirkel[2] from the Leucite Hills, Wyoming, is even richer in leucite. In addition to this mineral, it contains only a pale biotite, scattered needles of green augite, apatite, and a small quantity of magnetite. Kemp[3] has shewn, however, that the lavas forming these hills present considerable variation. In particular the leucite gives place to sanidine in various proportions, affording transitions to leucitophyre. From the variety containing leucite to the exclusion of sanidine (Wyoming type) Cross[4] has separated that in which both minerals are well represented (Orenda type). He has described also another rock consisting

[1] Washington, *Journ. Geol.* (1896) iv, 556–558 (Bolsena); *ibid.* (1897) v, 41, 42 (L. Bracciano), 46, 47 (Cerveteri), 245 (Rocca Monfina).
[2] *Micro. Petrogr. Fortieth Parallel*, 260, 261; pl. v, fig. 4; I, figs. 21–23.
[3] *Bull. G. S. Amer.* (1897) viii, 175–180.
[4] *A. J. S.* (1897) iv, 120–133, and in Diller, 186–191.

of diopside and yellow mica with a glassy base which has the composition of leucite (Madupa type).

A leucitite from the Bear-paw Mts of Montana[1] contains phenocrysts of augite and leucite in a ground-mass consisting essentially of minute skeleton leucites with very little interstitial glass.

Of *leucite-basalt* good examples come from the Eifel district (Fornicher Kopf, Hummerich, *etc.*). These have phenocrysts of olivine, augite, and often biotite, in a ground-mass which is always very fine-grained but rarely contains any glassy residue. It consists of predominating augite with leucite and often nepheline, while a little sanidine sometimes occurs interstitially.

Weed and Pirsson[2] have described specimens from the Bear-paw Mts, Montana. Here the leucites, up to $\frac{1}{50}$ inch in diameter, are turbid from alteration. The other phenocrysts are olivine and pale brown zoned augite, and these minerals occur abundantly in a ground-mass of magnetite grains, augite microlites, and what appears to be a colourless glass.

Leucite-basalt has been described from localities in New South Wales[3]. The abundant olivine has a somewhat peculiar character. This, with leucite and large ragged flakes of yellow mica, belongs to the earlier stage of consolidation, while the ground-mass of the rock is a finely-crystalline aggregate of leucite, yellowish-green augite, and magnetite, with occasionally a little glass.

The rocks rich in nepheline are almost always holocrystalline. A well-marked type is the doleritic *nephelinite* or nepheline-dolerite of Löbau in Saxony, a rock of comparatively coarse texture, with abundant nepheline. The augite is of a purple-brown pleochroic variety, with hour-glass or other zonary growth, and often idiomorphic (fig. 49). Locally the structure of the rock may become intersertal or, again, micrographic[4]. Besides the abundant nepheline, subordinate sanidine may

[1] Weed and Pirsson, *A. J. S.* (1896) ii, 144–148, with figures.
[2] *A. J. S.* (1896) i, 288–290.
[3] Judd, *M. M.* (1887) vii, 194, 195; Edgeworth David and Anderson, *Rec. Geol. Sur. N. S. W.* (1890) i, 159–162, pl. xxviii.
[4] Cohen (3), pl. xxxiv, fig. 2.

occur, and more rarely a plagioclase. The common iron-ore is a titaniferous magnetite, and apatite needles occur abundantly. In the otherwise similar type of Meiches, in the Vogelsberg (Hesse), leucite, in irregular grains crowded with apatite needles, becomes a prominent constituent. Both rocks shew transitions to nepheline-basalt, of finer texture, with less
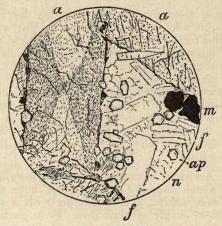
FIG. 49. NEPHELINITE (NEPHELINE-DOLERITE), LÖBAUER BERG, SAXONY; ×20.

The minerals shewn are nepheline (n), some felspar (f), purplish-brown augite (a) with hour-glass structure, magnetite (m), and apatite (ap), the rock being holocrystalline. The coming in of felspar marks a transition to the tephrite type [G 220].

nepheline and with abundant phenocrysts of olivine. The same is true of another well-known nephelinite, that of Katzenbuckel in the Odenwald (Baden). A typical nepheline dolerite has been recorded from Shannon Tier in Tasmania[1].

Another type ('basaltic nephelinite') occurs in the Grand Canary, etc., and by the coming in of plagioclase passes into the tephrites. It is of fine texture and much richer in augite

[1] Twelvetrees and Petterd, *Papers and Proc. R. S. Tas.* for 1898–9 (1900), 60–64.

than the preceding. Varieties, some rich in haüyne, occur in the Erzgebirge and in Bohemia. Rosenbusch's 'phonolitic' type is, on the other hand, poor in coloured minerals, and carries no augite-phenocrysts. In the frequent presence of ægirine-microlites, the abundance of idiomorphic nepheline, and the coming in of sanidine, this type approaches the phonolites.

The *nepheline-basalts*, much more widely distributed than nephelinites, shew less variety of character. They are typically holocrystalline rocks composed of nepheline, augite, and olivine, with some magnetite and apatite. Some contain biotite in addition to augite, and haüyne may accompany the nepheline[1]. Such rocks are known in Hesse and Thuringia, the Eifel, many parts of Saxony, Bohemia, the Cape Verde Islands, Brazil[2], and other districts of Tertiary and Recent volcanic rocks. The chief variation depends upon the coming in of melilite in addition to nepheline (*e.g.* Herchenberg and Bongsberg in the Eifel, several Saxon localities, *etc.*). Leucite is a less common accessory.

Several American examples have been described. From the Cripple Creek district, Colorado, Cross[3] notes a dyke very rich in olivine, augite, and magnetite, with a subordinate colourless base, chiefly of nepheline. From southern Texas Osann[4] describes a rock in which large olivines are abundant, with magnetite and small octahedra and grains of brownish-violet perofskite. The holocrystalline ground-mass consists of abundant augite-prisms, tabular crystals of faint yellow melilite with characteristic cross-fibration and 'peg-structure' (Ger. Pflockstructur), and aggregates of shapeless grains of nepheline. Felspar is entirely wanting. This rock is inter-mediate between nepheline-basalt and melilite-basalt.

In the true *melilite-basalts* nepheline is wanting or at most an accessory. Phenocrysts of olivine, augite, and biotite are embedded in a usually holocrystalline ground-mass of smaller

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[1] Fouqué and Lévy, pl. xlix, fig. 2.
[2] G. H. Williams, *A. J. S.* (1889) xxxvii, 186, 187 (Fernando de Noronha).
[3] *16th Ann. Rep. U. S. G. S.* (1895) part ii, 49, 50.
[4] *Journ. Geol.* (1893) i, 341–343.

biotite, zoned augite, sometimes olivine, and melilite. The last sometimes occurs also among the phenocrysts. Biotite is specially characteristic, and in the first generation may form quite large flakes. Rocks answering to this description are known from Hochbohl, near Owen, and Urach, in Wurtemberg: from Görlitz, in the Prussian Lausitz; as dykes on Alnö, an island off the coast of Sweden; *etc.* A good example, of Silurian age, is described from Ste Anne de Bellevue, near Montreal[1]. Here the phenocrysts are brown mica in large and abundant crystals, olivine more or less converted to hæmatite, and augite: the ground-mass is of mica, olivine, augite, magnetite, and melilite, with apatite and perofskite, the last a mineral rarely absent from such rocks. The melilite is the latest product of consolidation, forming imperfect crystals of tabular habit with the characteristic 'peg-structure.' A rock from Mannheim, N.Y.[2], differs from this chiefly in the absence of pyroxene, and both closely resemble the typical 'alnöite' of Alnö, off the coast of Sweden, which also contains augite in addition to the large phenocrysts of brown mica. A good melilite-basalt has been described from Shannon Tier in Tasmania[3].

The only rocks of this kind known in Britain are those described by Dr Flett[4] from the Orkneys, where they form dykes cutting the Old Red Sandstone and associated with others of camptonite and monchiquite. One from Rennibuster, near Kirkwall, has for phenocrysts large irregular plates of biotite, small serpentinized olivines, and some large idiomorphic crystals of augite. The ground-mass consists of abundant small augites of purplish-brown colour, idiomorphic melilite, and interstitial matter representing altered glass or perhaps nepheline. Another, from Naversdale near Orphir, has the melilite in allotriomorphic patches, shewing peg-structure. The mineral is often replaced by zeolites, calcite, *etc.* An allied type is described under the name melilite-monchiquite.

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[1] Adams, *A. J. S.* (1892) xliii, 269–279.
[2] Smyth, *A. J. S.* (1893) xlvi, 104–107; (1896) ii, 290–292.
[3] Twelvetrees and Petterd, *Papers and Proc. R. S. Tas.* for 1898–9 (1900) 60–64.
[4] *Tr. Roy. Soc. Edin.* (1900) xxxix, 892–898, pl. III, figs. 4–6.

D. SEDIMENTARY ROCKS.

UNDER the head of sedimentary rocks we shall include the stratified deposits formed for the most part, though not exclusively, under water by the accumulation of detritus and of fragmental material of volcanic origin, by organic agency, and by chemical action or the evaporation of saline solutions. The last clause includes the secondary cementing material of many fragmental rocks, as well as the less common deposits of rock-salt, *etc.*, which do not demand special notice.

The rocks exhibit great variety of composition and characters, and in the nature of the case do not admit of any very strict petrological classification. They will be treated mainly under four groups : the coarser detrital deposits (*arenaceous*), the finer detrital deposits (*argillaceous*), the rocks consisting essentially of carbonate of lime (*calcareous*), and the fragmental volcanic rocks (*pyroclastic* of some authors). In all, with the exception of some of the calcareous rocks, a fragmental or '*clastic*' structure is essentially present : this, with the bedded occurrence, may be taken as characteristic of the whole.

CHAPTER XVI.

ARENACEOUS ROCKS.

THE arenaceous rocks are typical fragmental ('clastic') accumulations, consisting of grains of one or more materials mechanically derived, to which may be added interstitial matter deposited in place. There is thus a distinction between original or 'allothigenous' constituents, derived from a distance, and secondary or 'authigenous' constituents formed after the accumulation of the grains. The fragmental nature of the rocks is usually evident to the eye, and the conditions of deposition in water may be indicated by an appearance of lamination, but this is rarely so well marked as in some argillaceous rocks.

The name *sand* (Fr. sable) is reserved for incoherent deposits : when compacted by some cementing medium, they become *sandstone* or *grit*. These last two words are often used synonymously, though different writers have employed them to mark various distinctions. If a distinction be made, it is perhaps best to name the round-grained rocks sandstones, and those with angular grains grits. Such epithets as felspathic and calcareous are used to describe the nature sometimes of the grains, sometimes of the cement : they usually need no explanation. The old term *greywacke* (Ger. Grauwacke) has been revived for a complex rock with grains of quartz, felspar, and other minerals and rocks, united by a cement usually siliceous. An *arkose* is a deposit derived directly from the destruction of granite or gneiss, and containing abundant felspar. A *quartzite* (of the type belonging here) is a rock consisting of grains chiefly of quartz with a quartz cement.

The coarsest clastic deposits, in which pebbles occur as well as grains, are named *conglomerate* or pudding-stone (Fr. poudingue) when the large fragments are rounded, and *breccia* (Fr. brèche) when they are angular. These rocks will require but little notice.

Derived grains[1]. Since most sands are derived directly or indirectly (*i.e.* through the medium of earlier sedimentary deposits) from the waste of igneous or crystalline rocks, the *most usual minerals* in sand-grains are those which figure largely in the composition of large areas of rock, such as granites, gneisses, and crystalline schists. But chemical processes tend to make a selection among these constituents; for the material is commonly affected by partial decomposition, either prior to the disintegration of the parent rock-masses, during transport, or subsequently to the accumulation of the clastic deposit. So the commonest constituents of sands are those abundant rock-forming minerals which are least prone to chemical changes, such as quartz and white mica. Felspars, augite, hornblende, and dark micas may occur plentifully in particular deposits, but are less characteristic of sands in general, while unstable minerals like olivine rarely occur among detrital material. Certain accessories, such as zircon and rutile, are widely distributed in sands, but only in small quantity. Others may be abundant locally, just as the modern sands on our coasts are found in particular localities to be rich in garnet, or flint, or tourmaline, or ilmenite (menaccanite)[2]. The admixture of few or many constituents depends on the extent and geological diversity of the drainage-area from which the material was derived. River- and lake-sands usually shew less variety than those of marine origin[3].

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[1] For much information on sand-grains see Sorby, *Presid. Address*, *Q. J. G. S.* (1880) xxxvi, *Proc.* pp. 47–65; also *Anniv. Address Micro. Soc.* (1877) *Monthly Micro. Journ.*

[2] The heavier accessories may be separated from loose sands by levigation in water, as described by Mr Dick, *A New Form of Polarising Microscope* (1890), 41–45. A useful adjunct for this purpose is the 'batêa' or Brazilian miner's pan: see Derby, *Proc. Rochester Acad. Sci.* (1891) i, 198–206. For a dry method, see Carus-Wilson, *Nature* (1889), xxxix, 591. For an example of a systematic investigation, see Retgers on the dune-sands of Holland, *M. M.* xi, 113, 114 (*Abstr.*).

[3] See Julien and Bolton, *Proc. Amer. Assoc.* (1884) 413–416.

Some coarse-grained deposits contain composite *rock-frag-ments, e.g.*, a piece consisting of quartz and felspar with the relations characteristic of granite. Other sandstones have numerous fragments of lava. Recent deposits near the volcanic islands of the Pacific sometimes consist wholly of rolled fragments of lava, pieces of decomposing volcanic glass (palagonite), small chips of pumice, *etc.* By admixture of material of *directly* volcanic origin these volcanic sands graduate into tuffs.

The accumulations composed mainly or entirely of organic fragments (shell-sands, coral-sands, *etc.*) are more conveniently placed with the limestones.

The *form and superficial characters* of sand-grains, best studied by mounting the material dry or in water, may depend upon the properties of the individual minerals and their mode of occurrence in the parent-rocks; upon the effects of attrition during transport; and sometimes upon crystalline growth subsequent to the accumulation of the deposit. Grains of felspar, hornblende, *etc.*, usually have their boundaries partly determined by the cleavages of the mineral; mica tends to form flat flakes or scales; minerals like zircon and anatase, which in the parent-rock built small well-formed individuals, often preserve their form intact. They are probably released in some cases by the destruction in the sand itself of an enclosing mineral, such as biotite. Quartz breaks into fragments of irregularly angular outline. If originally of interstitial occurrence (*e.g.* in a granite) it partly retains its highly irregular contour, and the minor irregularities produce a rather opaque appearance on the surface. Quartz-grains from a fine mica-schist, on the other hand, tend to flaky and lenticular shapes.

The degree of *rounding* produced by attrition during transport depends on the hardness of the mineral, but also on the nature and duration of the mechanical agencies involved. Large grains are often more rounded than small (fig. 50). Marine sands are in general more round-grained than those of rivers and lakes, while wind-borne sands, such as those of deserts, are still more rounded by friction[1]. Only in

[1] For illustrations see *Tr. Edin. G. S.* (1897) vii, pl. xi, fig. 1; xix, figs. 2, 3.

these last are the smallest grains ever found to be well rounded.

It is usually possible to form some opinion as to the source or *sources of the derived material* of a sand. The minerals identified give a clue to the parent rock or rocks, and special features in the minerals may also afford information. Thus the existence of fluid-, glass-, or other cavities in crystal-fragments, the presence of rutile-needles in quartz-grains, *etc.*, may tell us whether the minerals in question originally formed part of a plutonic, a volcanic, or a metamorphic rock, or of several different rocks[1]. Too much stress must not be laid on the rounding of grains as indicating the distance of their source. Long-continued drifting to and fro within a limited area may cause more attrition than many thousand miles of travel in one direction : further, friction is much more effective under subaërial than under subaqueous conditions. Again, sand-grains must often be furnished ready-made by the destruction of older arenaceous deposits.
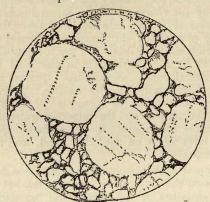
Fig. 50. 'Top Grit' or uppermost bed of the Quartzite Series, near Inchnadamff, Sutherland ; × 20:

shewing small angular quartz-grains occupying the interstices between the larger rounded ones [1665].

[1] See, *e.g.*, Mackie's investigation of the Old Red Sandstone of Eastern Moray, *Tr. Edin. G. S.* (1897) vii, 148–172.

The *coarseness or fineness* of sandstones may vary considerably. The sifting action of running water tends to collect in one place grains of roughly equal dimensions, but some sandstones contain grains of two very different sizes, the smaller occupying the interspaces between the larger (fig. 50). A very common size for the grains of quartz and felspar in many sandstones is from ·01 to ·03 inch[1].

Authigenous constituents. In addition to the clastic grains, sandstones and grits contain material deposited upon the surfaces of the grains, or filling in partially or wholly the interstices between them, and thus serving to bind them into a coherent rock. Whether formed by the recrystallization of calcareous or other matter laid down with the detritus, by the redeposition of material dissolved from the grains themselves, or by the introduction in solution of some extraneous substance, this cement must be regarded as formed in place, and its accumulation constitutes a new chapter in the history of the rock. The cementing medium itself is usually calcareous, ferruginous, siliceous, or some mixture of these.

The *calcareous cement* has probably been in most cases deposited in the form of mud, comminuted shells, *etc.*, with the original grains, but it becomes effective as a binding material only after some amount of solution and redeposition, which commonly gives it a more or less evident crystalline texture. Exceptionally a crystalline growth of calcite may enclose grains in ophitic or pœcilitic fashion, as in the Fontainebleau Sandstone of the Paris Miocene, but usually the calcareous cement is strictly interstitial, and it does not always fully occupy the interspaces between the grains. In rare cases other salts, such as gypsum and barytes, may serve as a cement.

Many sandstones are cemented by *ferruginous* matter or a mixture of ferruginous and calcareous. The red oxide and the brown hydrated oxide of iron occur in this way. Frequently the oxide forms a thin coating or pellicle round each grain of sand. This pellicle can be removed by acid, leaving the grains colourless.

[1] See Bonney, *Rep. Brit. Ass.* for 1886, p. 601, and *Nature* (1886), xxxiv, 412.

The clayey material (kaolin, very fine mica, *etc.*), which occurs interstitially in some sandstones, is probably to a great extent authigenous, representing the decomposition of felspar grains, *etc.* Similarly a chloritic mineral is not uncommon, and may be derived from the destruction in place of such minerals as hornblende and biotite.

In the tougher sandstones and grits the cementing matter is in the main *siliceous.* When the grains are angular and of various sizes, the interspaces may be very small, and the interstitial silica, concealed by the grains and perhaps by kaolin dust or iron-staining, may be difficult to observe. In more or less porous rocks, the little cementing matter required may be provided by some slight solution of the quartz-grains themselves at the points where they press on one another, as suggested by Mr Wethered for the sandstones of the Bristol coalfield.

When spaces have existed between the original grains, it is usually seen that the siliceous cement has been deposited in crystalline continuity with the original quartz as a *new outgrowth of the clastic grains.* The secondary enlargement of
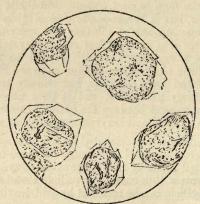
Fig. 51.   Quartz-grains from Penrith Sandstone, Penrith Beacon, Cumberland ;   × 20 :

shewing a secondary outgrowth of quartz with crystal-faces [1920].

the grains is verified by the new material extinguishing simultaneously with the old between crossed nicols. Again, many sandstones which have not been compacted into hard rocks exhibit a similar new growth on the surfaces of the grains; and in this case (fig. 51) the added material often shews good crystal faces[1] ('crystallized sand'). The enlargement is commonly clearer than the nucleus, and the division between them is marked by a line of dusty inclusions or by a thin partial coating of some deposit older than the outgrowth. Though characteristic of quartz, a similar outgrowth is occasionally found on fragments of felspar[2] and hornblende[3].
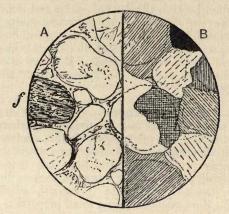
Fig. 52.　Quartzite, Stiperstones, Shropshire; × 50:

A in natural light, B between crossed nicols. The grains are of rolled quartz with an occasional turbid felspar (f), and the interspaces are filled by a secondary outgrowth of quartz from the grains. The shading is diagrammatic, to indicate different interference-tints. A composite grain in the centre shews outgrowths from both portions [224].

[1] Sorby (*Address cit. supra*, 62–64). For figures see R. D. Irving, *5th Ann. Rep. U. S. Geol. Sur.* (1885) pl. xxx; Irving and Van Hise, *Bull. No.* 8 *U. S. Geol. Sur.* (1884) pl. ii; Phillips, *Q. J. G. S.* (1881) xxxvii, pl. ii.

[2] Irving, *l. c.*, pp. 237–241, and 44–47.

[3] Van Hise, *A. J. S.* (1885) xxx, 232–235.

In less frequent examples new-formed quartz has a radial arrangement about original grains, or is oriented independently. Again, a cement of cryptocrystalline or chalcedonic silica is known in some rocks. This, however, is rather characteristic of volcanic sandstones and conglomerates in regions of hot-spring action : *e.g.*, in the Yellowstone Park rolled fragments of obsidian and rhyolite are thus cemented into a hard rock.

When a deposit originally a quartz-sand becomes completely compacted by an interstitial cement of secondary quartz, the result is a *quartzite* of the ordinary type. Such rocks often consist wholly, or almost wholly, of quartz, but in a thin slice the distinction between the derived grains and the interstitial cement comes out clearly. Usually the new quartz is a crystalline outgrowth from the grains, the space between two grains being occupied by quartz, of which part is in continuity with one grain, part with the other. Between crossed nicols the slice therefore assumes the appearance of an irregular mosaic[1] (fig. 52).

Some British examples[2]. The forms and general characters of sand-grains may be studied in modern deposits[3] and in the sands, not yet compacted into sandstone, of the later geological formations. Among the materials quartz, as a rule, largely predominates, but the sands of our modern coasts are locally rich in other minerals, such as flint, garnet, tourmaline, magnetite, ilmenite (Cornwall), silicified wood (Eigg), *etc.* Most sands contain a small proportion of certain heavy minerals, which can be separated by special methods. In the fine-grained Bagshot Sands of Hampstead Heath and

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[1] For coloured figures see Teall, pl. xlv, fig. 2 ; xlvi, fig. 1 ; Irving (*cit. supra*), pl. xxxi ; Irving and Van Hise, *On Secondary Enlargements of Mineral Fragments* (1884), *Bull. No.* 8 *U. S. Geol. Sur.* pl. iii–vi.

[2] Interesting information concerning British arenaceous rocks is contained in Sorby's *Presidential Address*, quoted above, and earlier papers (*Proc. Yorks. Geol. and Pol. Soc., etc.*). See also J. A. Phillips, *Q. J. G. S.* (1881) xxxvii, 6–27 ; Bonney, *Nature* (1886), xxxiv, 442–451, and *Rep. Brit. Ass.* for 1886, 601–621.

[3] For an account of the sands and other deposits now forming in the Irish Sea see Herdman, *Rep. Brit. Ass.* for 1894, 328–339, and *Pr. Liverp. G. S.* (1894) vii, 171–182 ; Herdman and Lomas, *ibid.* (1898) viii, 205–232.

of High Beech in Essex Mr Dick[1] found up to 4 per cent. of dense minerals, including magnetic iron ore, zircon, rutile, and tourmaline. Many sands contain small quantities of these and other special minerals (garnet, cyanite, anatase, etc.). The basal bed of the Thanet Sands contains 20 per cent. of flint in sharply angular chips, with quartz, glauconite, and numerous other minerals[2]. The flint is of course derived from the Chalk.

The form of quartz-grains depends in great measure upon their source, whether directly from crystalline rocks or from older sandstones or grits. Thus the Glacial sands of the York-shire coast, which must come chiefly from crystalline rocks, have sharply angular shapes, and the grains on the modern beaches of that coast, most of which are doubtless washed out of the Glacial accumulations, are scarcely more abraded. On the other hand, modern sands on the south-east coast of England, derived very largely from older arenaceous deposits, have a considerable proportion of rounded grains. On the north-west coast both Glacial and modern sands often contain extremely rounded grains, explained as being derived from the 'millet-seed' sandstones of the Trias, but these are mixed with angular quartz in various proportions. The grains of the sand-dunes on our coasts are much less rounded than those of desert sands.

The Mesozoic formations afford numerous examples of calcareous and ferruginous cements. Thus the Calcareous Grits of Yorkshire have a cement of calcite, often stained or mixed with iron-oxide, and some of them might with equal propriety be named impure gritty limestones. The Kellaways Rock has usually a ferruginous cement (fig. 53, B). In the Lower Greensand of the eastern counties the cement is sometimes largely ferruginous, with a little interstitial quartz ('carstone' of Hunstanton), but in many cases is of granular calcite, which may be iron-stained. Occasionally the calcite builds large plates enclosing many of the partly rolled quartz-grains (Spilsby in Lincolnshire, Copt Point near Folkestone).

[1] *Nature* (1887), xxxvi, 91, 92 ; Teall, pl. xliv ; *cf.* Fouqué and Lévy, pl. iv.
[2] Miss Gardiner, *Q. J. G. S.* (1888) xliv, 755–760.

Many of these rocks have little grains of bright green glauconite with various rounded shapes, explained as casts of foraminifera. Another feature is the occurrence of little round oolitic grains of dark brown iron-ore ('carstone' of Hunstanton, and Roslyn Hill, Ely). These grains have a concentric-shell structure, and, when dissolved in acid, leave a siliceous skeleton (fig. 53, *A*). Zircon crystals are among the denser constituents[1]. The best British examples of glauconitic sands come from the base of the Cretaceous in Antrim. The glauconite grains, unusually large and abundant, are all casts of foraminiferal chambers[2]. The glauconitic sands of the Upper
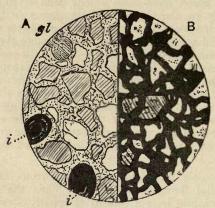
Fig. 53; × 20.

A. Calcareous grit in Lower Greensand, Roslyn Hill, Ely: shewing subangular quartz, with a few glauconite casts of foraminifera (*gl*), and derived oolitic grains of dark brown iron-ore (*i*), cemented by a matrix of granular calcite [1799]. *B.* Ferruginous grit, Kellaways Rock, South Cave, Yorkshire: shewing angular quartz-grains in a cement mainly of iron-oxide [1797].

Greensand in Wiltshire, Dorset, Devon, and the Isle of Wight are chiefly of coarse quartz-sand with fragments of felspar and

[1] Hume, *Q. J. G. S.* (1894) l, 679 (Bargate).
[2] *Ibid.* (1897) liii, 569–571.

mica, but large glauconite grains are abundant. There is often a calcareous cement[1].

The Upper Palæozoic grits and sandstones of this country often have a cement largely ferruginous or consisting of iron-oxide and quartz. In the Devonian of South Devon are fine-grained sandstones which, with predominant quartz, have little flakes of mica, some felspar, and small granules of tourmaline, indicating the source of the material: the interstitial matter is for the most part ferruginous. Much of the Old Red Sandstone shews the investing pellicle of ferric oxide around each grain.

This latter feature and numerous other points of interest may be studied in many parts of the New Red Sandstones. In particular, quartz-grains with a secondary outgrowth having crystal-faces are common at various horizons of the Keuper and Bunter[2] of Shropshire, Cheshire, etc., and are also exceptionally well exhibited in some coarse-grained beds of the Penrith Sandstone (Penrith Beacon, Cumberland), (fig. 51). In some cases a pellicle of iron-oxide coats the new crystal-growth, and must then be long posterior to the date of the strata. Red sandstones are often of quite yielding consistency, even when the interstices are occupied by quartz. This is because of the coating of iron-oxide intervening between the interstitial quartz and the original grain. By treatment with acid, the irregularly shaped patches of interstitial quartz were isolated by Mr Phillips from the 'millet-seed' sandstones of the Trias. In these beds the perfectly rounded form of the original grains is attributed to their having been true desert-sands[3].

Many Carboniferous grits have sharply angular grains, and were probably derived directly from crystalline rocks. The

[1] On these and other arenaceous rocks of the Upper Cretaceous see W. Hill in *Mem. Geol. Sur., Cret. Rocks Brit.*, vol. i. (1900) chap. xxv.

[2] For descriptions of Triassic sandstones from the Vale of Clwyd, Cheshire, and Lancashire, see Morton, *Geology of Liverpool* (2nd ed. 1891), 129–132; M. Reade, *Pr. Liv. G. S.* (1892) vi, 374–386; Dickson and Holland, *ibid.* (1896) vii, 449–451; Moore, *ibid.* (1898) viii, 241–265; Lomas, *ibid.* 265–267, pl. xiii.

[3] *Cf.* Mackie on the Reptiliferous Sandstone of Elgin, *Tr. Edin. G. S.* (1897) vii, 166, pl. xix, fig. 2.

coarse-grained Millstone Grit of south Yorkshire[1] has highly irregular quartz-grains poor in fluid-cavities. There is not much fresh felspar, but argillaceous matter between the quartz-grains seems to represent it. The hard 'ganister' has angular quartz-grains which fit so closely together as to obscure the small amount of siliceous cement, and the same is true of the grits of the Bristol coal-field. In some beds in the Coal-Measures numerous flakes of muscovite lying parallel to the lamination impart a fissile character to the rocks (Bradford Flags, *etc.*). The spaces between the grains are often obscured by kaolin. Kaolin and relics of reddish orthoclase, with a little mica and sometimes tourmaline, are found in the Millstone Grit of south-west Lancashire[2], which consists mainly of angular quartz-grains of very variable size (·2 to ·005 inch) with crystalline outgrowths not very common. In the Cefn-y-Fedw Sandstone of Denbighshire and Flintshire[3] the grains are angular to rounded, and more often have secondary outgrowths with crystal-faces.

The Lower Palæozoic and older arenaceous rocks are, as a rule, thoroughly compacted, the cement being for the most part siliceous. Mr Phillips found the quartz-cement of various Cambrian and Silurian grits (Barmouth, Harlech[4], Aberystwith, Denbighshire) permeated by a moss-like growth of a green chloritic mineral. Both coarse and fine-textured rocks are included. The quartz-grains are angular or partly rounded, and frequently contain needles of rutile and tourmaline: fluid-pores are present in some, absent in others. Some of the grits have plenty of felspars, while pyrites, garnet, and micas are occasionally noted. Specimens of the grits of Skiddaw and of the Isle of Man (Santon) shew fragments of slate and lava among the partly rolled quartz and turbid felspars. The Ingleton rock in Yorkshire is a grit containing volcanic material as well as grains and pebbles of quartz, felspars, and various

[1] Sorby, *Pr. Yorks. Geol. Pol. Soc.* (1859) iii, 669–675. On the Millstone Grit of the Forest of Dean see Wethered, *Pr. Cottesw. F. N. Club* (1883), viii, 25–27, with plates.

[2] Morton, *Proc. Liverp. G. S.* (1887) v, 280–283.

[3] *Ibid.* 271–279.

[4] *Cf.* Greenly, *Tr. Edin. G. S.* (1897) vii, 254–258.

lavas[1]. Volcanic grits of finer texture occur in the upper part of the Ordovician near Shap Wells, Westmorland, and these contain also calcareous matter.

The older sandstones of the Bangor and Caernarvon district and of parts of Anglesey are rather coarse-grained, consisting of well-rounded to subangular quartz with plenty of felspar. The latter mineral is often decomposed, and its clayey decomposition-products wedged in between the quartz-grains, obscuring the siliceous cement (fig. 54). Some of the rocks, however, have comparatively fresh felspar : a Silurian grit at Drys-lwyn-isaf, south of Parys Mountain, consists almost wholly of grains of oligoclase closely packed together. The prevalent type of the Torridon Sandstone is an example of a coarse sandstone rich in felspar. Besides rolled quartz-grains often composite, it has others of microcline and fragments of quartzite and pegmatite.
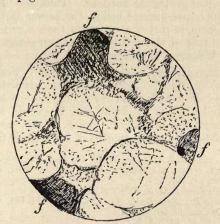
FIG. 54. SANDSTONE, FACHELL, NEAR LLANDEINIOLEN, CAERNARVON-SHIRE ; × 20.

Besides the well-rolled quartz-grains with many rows of fluid-pores, felspar is represented (*f*). This is largely decomposed, the resulting clayey material being squeezed between the quartz-grains [282].

[1] Tate, *Rep. Brit. Ass.* for 1890, 800.

The best examples of *quartzites* in England are those of Hartshill in Warwickshire and the Lickey Hills in Worcestershire, probably of pre-Cambrian age[1], and the Stiperstones in Shropshire (Ordovician)[2]. All these consist essentially of rolled quartz-grains, usually about ·02 to ·03 inch in diameter, with only very subordinate felspar, united by a clear quartz-cement which is of the nature of a crystalline outgrowth from the grains (fig. 52). A series of quartzites forms the lower part of the Cambrian in the Assynt district, Sutherland. Some beds contain pebbles, and are indeed cemented conglomerates. The uppermost bed ('Top Grit') shews large well-rolled quartz-grains, about ·05 inch in diameter, with smaller subangular grains between them. The remaining space, occupied by the siliceous cement, is obscured by opaque dust (fig. 50). Good quartzites, probably of Cambrian age, occur at Bray Head and Howth near Dublin[3]. In some districts quartzites have been formed at higher geological horizons. Thus, the 'Moor Grit,' a conspicuous coarse-grained bed in the Lower Oolites of the Yorkshire moors, is rather a quartzite than a grit; and the same is often true of the well-known 'sarsen stones' or 'greywethers' of Wiltshire, Dorset, *etc.*[4]

Of American arenaceous rocks a number of typical examples are described by Diller[5]. Interesting secondary outgrowths of clastic grains, often with good crystal-facets, are seen in the Potsdam Sandstone[6] of Michigan and Wisconsin and in the Huronian quartzites[7] of the same region. Conglomerates from Minnesota shew similar outgrowths of hornblende fragments[8].

[1] Teall, pl. XLV, fig. 2, XLVI, fig. 1, and *Pr. Phil. Soc. Birm.* (1882) iii, 194–202 ; Watts, *Summary of Progress Geol. Sur.* for 1897, 68, and *Pr. Geol. Ass.* (1898) xv, 393, 397.

[2] Rutley, *Pr. Liverp. G. S.* (1885) v, 381.

[3] Sollas, *Sci. Pr. Roy. Dubl. Soc.* (1892) vii, 174–184, pl. xv ; *Pr. Geol. Ass.* (1893) xiii, 91–93, pl. III.

[4] *Cf.* Judd, *G. M.* 1901, 1, 2.

[5] Diller, *Educ. Series Rock-Specimens*, 59–64, 74–84, pl. IX, X, XIII.

[6] Irving, *A. J. S.* (1883) xxv, 401–411 ; *5th Ann. Rep. U. S. Geol. Sur.* (1885) pl. XXX ; Diller, 79, 80, pl. X. A number of figures of Potsdam Sandstones are given by Buckley, *Build. and Ornam. Stones, Wis., Bull. 4 of Wis. Geol. and Nat. Hist. Sur.* (1898) pl. LXIV–LXVII.

[7] *5th Ann. Rep. U. S. Geol. Sur.* (1885) pl. XXXI, and *Bull. No. 8 U. S. Geol. Sur.* (1884) pl. III–VI.

[8] Van Hise, *A. J. S.* (1885) xxx, 231–235.

CHAPTER XVII.

ARGILLACEOUS ROCKS.

THE name *clay* is used for argillaceous deposits which still retain enough moisture to be plastic. By the loss of most of their uncombined water and by other more important changes these pass into mudstones, shales, and slates. Of these terms, *mudstone* is correctly used when the rock has no marked fissile character, *shale* when it splits along the original laminæ of deposition, and *slate* when the original lamination has been superseded as a direction of weak cohesion by a new structure (slaty cleavage, Fr. schistosité, Ger. Transversalschieferung). The Continental geologists do not, as a rule, observe this distinction, but include shales and slates under the same name (Fr. schiste, Ger. Schiefer, Norw. skiffer).

Among slates it has been usual to distinguish *clay-slates* (Thonschiefer, lerskiffer), in which the material was supposed to be largely detrital matter without important new formation of minerals, and *phyllites* (Fr. phyllade), in which the rocks are largely or totally reconstituted in place (aided, at least, by pressure). It is now becoming evident, however, that in clay-slates, and even in clays and shales, there has often been a considerable amount of mineral change in place ; so that no very sharp line can be drawn between clay-slates and phyllites. The typical glossy phyllites are essentially mica-schists on a small scale, and may be described as micro-crystalline schists. We shall find it convenient to include them here, although we thereby anticipate their place under the head of dynamic metamorphism.

Constituent minerals. Owing to the extremely small dimensions of the elements, it is usually a matter of great difficulty to identify with certainty all the constituents of clays, shales, or slates. Speaking generally, these constituents include some of derived or detrital origin (allothigenous), which were either primary minerals or decomposition-products in the parent rock-masses, and others of secondary origin, formed in place (authigenous). As regards the latter, doubt may exist in particular cases as to how far the secondary recombinations have been induced by pressure (dynamic metamorphism). In many fine-grained slates no constituents are seen which can be set down with confidence as purely detrital. In all cases very thin sections and high magnifying powers must be used. Some of the denser accessory minerals may be isolated from powder by heavy solutions, or merely by washing[1].

The detrital elements may include granules of *quartz*, and less frequently of *felspars*, and scales of *mica*, with minute crystals of such accessories as *zircon*. The little flakes of biotite shew more or less decomposition : Mr Hutchings finds that they give rise, not to chlorite, but to *epidote* in minute superposed tablets of light yellow colour. The iron-oxides separate out as *limonite*. *Carbonates* may occur in varying proportion. Many argillaceous rocks contain a considerable quantity of *carbonaceous matter*, finely granular and for the most part opaque : slices may be bleached by incineration on platinum foil. The *pyrites* which occurs in many slates, sometimes in relatively large crystals, is of secondary origin, and is perhaps due to the reduction of iron-compounds in the presence of organic matter. The *glauconite* of some argillaceous deposits has also been formed in place[2].

The ordinary fine-grained argillaceous rocks consist in considerable part of an exceedingly fine-textured base or paste, very difficult to resolve, in which any truly detrital

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[1] *Cf.* Teall, *M. M.* (1887) vii, 201–204. For a method of studying fine incoherent sediments, see Hutchings on Sediments dredged from the English Lakes, *G. M.* 1894, 300–303.

[2] See W. Hill on the micro-structure and mineral ingredients of the Gault, *Mem. Geol. Sur., Cret. Rocks Brit.*, vol. i (1900), chap. xxiv.

elements or their evident alteration-products are embedded.
The nature of this paste has not yet been made out in any
large number of cases. It was formerly regarded as consisting
essentially of hydrated silicate of alumina (kaolin), *etc.* Care-
ful studies of various clays, shales, and slates lead, however,
to the conclusion that the material is to a great extent a
very finely divided *micaceous substance* of secondary origin ;
and this is confirmed by chemical analyses of the rocks,
which often shew a considerable content of alkalies. Ac-
cording to Mr Hutchings[1], this main constituent of the
fine-grained base is in ordinary clays and shales an impure,
pale, greenish-yellow mica ; while in slates, where crystalline
reconstruction is more advanced, it has given place to a
mixture of pure muscovite and a chlorite-mineral, the two
often in very intimate association. In rocks not completely
regenerated there may be observed in addition much indeter-
minable finely granular matter, which may be conjectured to
represent the finest powder of quartz, felspar, *etc.*, and perhaps
kaolin or other products. A highly characteristic feature of
the paste is the presence of an enormous number of minute
needles of *rutile* ('clay-slate-needles')[2]. On account of their
very small breadth and very high refractive index, the needles
often appear as opaque lines, but the larger ones may be
transparent. The rutile is generally regarded as of secondary
origin, being produced in place in association with the mica,
etc., the titanic acid being furnished by derived biotite. Since
the changes which gave rise to these secondary products have
operated in clays as well as in slates, they cannot be held to
imply any advanced dynamic metamorphism, but they may
still be favoured by pressure.

Many slates seem to shew by their chemical composition
the presence of secondary free silica (in addition to any evident
detrital quartz which they may contain). This is sometimes
seen as a *quartz-cement*, tending to form little veins and

[1] *G. M.* 1896, 312, 313. This author points out the advantages of
cutting slices from a specimen previously ignited to redness. The
resulting dehydration causes the chloritic substance to become more
opaque, or assume a deeper colour, while impure mica is less affected,
and the pure muscovite unchanged.

[2] *Cf.* Teall, *M. M.* (1887) vii, 201–204 ; Cohen (3), pl. iii, fig. 4.

patches; in other cases *opal* has been supposed to occur, and indeed amorphous silica may be dissolved out by caustic potash.

In some rocks, especially the Glacial tills, we must suppose that a large part of even the most impalpable material is of detrital origin. Thus in the tills of the Boston basin, Massachussetts, Crosby[1] found that about four-fifths of the finest grade of material was not what is commonly understood by clay, but what he terms 'rock-flour,' *i.e.* the most minute particles of pulverised quartz and other rock-forming minerals, not chemically decomposed.

Structures. Argillaceous rocks in general have a parallel arrangement of their constituent elements which is usually sufficiently marked to impart a fissile character to the mass. Slices parallel and perpendicular to the direction of fissile structure should be compared. In shales a large proportion of the minute constituent elements lie with their flat faces or long axes parallel to the layers of deposition. In true slates, *i.e.* rocks with a superinduced *cleavage-structure*, they have taken up a new direction along planes (cleavage-planes) perpendicular to the maximum compression by which the rock has been affected.

The effect of this compression, accompanied by a certain partially compensating expansion along the cleavage-planes, is well seen in the deformation of concretionary spots of colour, *etc.* A spherical spot becomes distorted into an ellipsoid. A hard unyielding body, such as a crystal of pyrites or magnetite embedded in the rock, gives rise to curious phenomena. The matrix flows past the crystal, leaving a roughly eye-shaped space[2]. Such crystals have in many cases been originally coated with an envelope of chlorite, which adheres to the matrix and is torn away from the crystal. The intervening space is subsequently filled by infiltration with crystalline quartz (fig. 55, *A*).

Various structures, of frequent though local occurrence in

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[1] *Proc. Bost. Nat. Hist. Soc.* (1890) xxv, 115–172.
[2] *G. M.* 1889, 396, 397.

fine-grained beds, may be styled '*false*' *and incipient cleavages*[1]. They consist sometimes in a parallel system of microscopic faults, sometimes in a regular system of minute folds. These
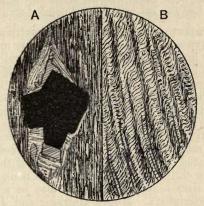
Fig. 55.

A. Slate with crystal of pyrites, Penrhyn, near Bangor; × 5. The crystal is surrounded by an 'eye' of chlorite and quartz, as described. The mass of the slate contains little light spots, which have been deformed into an elliptic shape [501]. *B.* False cleavage in Skiddaw Slate, Brownber, near Appleby; × 20. The system of minute parallel folds causes a direction of weakness almost equivalent to cleavage [913].

often give a tendency to the rock to split along definite planes, *viz.* the fault-surfaces or the limbs of the folds (fig. 55, *B*). Dr Sorby[2] has shewn that such structures may be a step towards a true slaty cleavage. They may also, however, occur as later structures crossing a true cleavage (*e.g.* in various Ardennais slates and phyllites), and they are common in some fine-textured mica-schists. They are often interesting as reproducing on a minute scale the characteristic structures of mountain-ranges, such as the gradual passage of an over-fold into an overthrust fault, the relation of faults to anticlines,

[1] *Rep. Brit. Ass.* for 1885, 836–841. Some writers have used the terms 'close-joints cleavage' (Sorby), 'Ausweichungsclivage' (Heim), and 'strain-slip-cleavage' (Bonney) for structures of this kind.
[2] *Q. J. G. S.* (1880) xxxvi, *Proc.* 72, 73.

etc. A frequent result of shearing movement in finely laminated rocks is the formation of minute oblique folds inclined at about 45° to the lamination : these are pushed over until at about 30° they pass into little faults, and the faults may be further pushed over until they are lost in a general parallel-structure.

Illustrative examples. Before describing some of the commoner types of argillaceous rocks, we may mention one of which very little is known among consolidated strata. It is represented among deposits now forming by the *abyssal red clay* which covers large areas of the ocean-floor below a depth of 2200 fathoms. This deep-sea clay is derived mainly from the destruction of volcanic products by the chemical action of sea-water. Minute fragments of volcanic rocks and minerals are mixed with decomposition-products and with a few siliceous organisms (radiolarians, *etc.*). The brownish-red colour is due to disseminated limonite. Minute crystals of the lime-zeolite phillipsite or christianite are common[1], and manganese-nodules of various sizes occur. There may also be a few corroded tests of foraminifera. Messrs Harrison and Jukes-Browne[2] found that about two-thirds of a typical 'red clay' consists of fine argillaceous matter derived from the destruction of basic pumice or palagonite. The rest is chiefly disintegrated (but not decomposed) acid pumice ; while 5 *per cent.* of the clay is matter of organic origin, principally colloid silica. The red and yellow deep-sea clays of the Tertiary in the Barbados have a very similar constitution[3]. Other rocks comparable with the abyssal red clay have been described from the Solomon Islands[4] and from Trinidad[5].

These deep-sea argillaceous deposits have characters which distinguish them from those derived from the waste of land-areas. The particles are of excessive minuteness and markedly angular in shape[6]. The minerals recognizable are those most

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[1] See Murray and Renard, 'Challenger' Report, *Deep-Sea Deposits* (1891), pl. XXII.

[2] *Q. J. G. S.* (1895) li, 314–321.

[3] *Cf.* Miss Raisin, *Q. J. G. S.* (1892) xlviii, 180–182.

[4] Guppy, *The Solomon Is., their Geology, etc.* (1887) 81, 82.

[5] Gregory, *Q. J. G. S.* (1892) xlviii, 539.

[6] Murray and Renard, *l. c.*, pl. XXVI, XXVII, figs. 1–4 ; contrast with fig. 5.

common as constituents of volcanic rocks, such as felspar and augite, rarely quartz; while such minerals as zircon, tourmaline, *etc.*, are absent. Usually a very large proportion of the material consists of angular chips of volcanic glass and elongated fragments derived from the breaking up of pumice with capillary pores.

As another somewhat peculiar type of clay may be mentioned the *china-clay* of Cornwall, which seems to consist essentially of the mineral kaolin[1]. This, in its most recognizable form[2], builds minute colourless scales, sometimes with hexagonal outline, and of such refractive index and birefringence as closely to resemble mica. It appears, however, from Mr Collins's account[3] that these distinct flakes do not form any large part of the finely divided material in the typical occurrences in Cornwall. Besides quartz, mica, and other impurities, tourmaline is found in some rocks composed largely of kaolin, and its production was perhaps connected with the process of 'kaolinization' of felspathic rocks[4]. In addition to the proper china-clays, formed more or less *in situ*, there are derived clays of similar composition, such as those of Bovey Tracey.

Under certain conditions, not yet made clear, it appears that decaying igneous rocks may be deprived more or less completely of their combined silica, as well as the alkalies and dioxides, the alumina remaining in the form of hydrate, often with ferric hydrate. The *bauxite-clays* of Antrim are of this type, and probably result from the subaërial decomposition of basalt almost in place. Where quartz-bearing rocks have been subjected to this kind of change, quartz-sand remains mixed with the aluminium and iron hydrates. Much of the so-called *laterite* of India and other tropical countries seems to be of this nature.

[1] Some writers apply the name kaolin to the clay itself, and use 'kaolinite' for the mineral. Collins uses the name 'carclazite' for the true kaolin-clay and 'petuntzite' for a less altered variety still retaining relics of undestroyed felspar.

[2] See Dick, *M. M.* (1888) viii, 15–27, pl. III.

[3] *M. M.* (1887) vii, 205–214 ; Teall, pl. XLIV, fig. 5.

[4] Butler, *M. M.* (1887) vii, 79, 80 ; *etc.*

We pass on to the consideration of clays and slates of more ordinary constitution, selecting only a few examples which may be regarded as typical[1].

A minute study of typical argillaceous rocks has been made by Mr Hutchings in the case of the *fire-clays* of the Newcastle Coal-measures[2]. The rocks are laminated, and include coarser and finer beds. The material of true detrital origin is most abundant in the coarser beds. It seems to be derived from the destruction of granite, and consists of granules of quartz averaging ·002 to ·003 inch in diameter, granules of felspar, biotite flakes from ·01 inch downward, with the epidotic alteration, less abundant muscovite, and accessory zircon, *etc.* Besides these there is a paste, in which minute scales of secondary mica and needles of rutile are the recognizable elements. The *shales* of the South Wales coal-field[3] were found to present similar characters, though much obscured by organic pigment. A considerable amount of clastic muscovite, and occasionally biotite, remains with the quartz-granules, and the paste of newly-formed micaceous material has the usual rutile-needles.

The Culm-measure shales of Bude in Cornwall[4] are derived from the waste of granite (in part with tourmaline) and crystalline schists. They appear to have undergone more change *in situ* than the preceding.

The Cambrian *roofing-slates* of North Wales represent a more advanced stage of secondary change, both structural and mineralogical. They possess a strong cleavage-structure, passing indifferently through the layers of original deposition, and the more altered of them have the glossy aspect of fine-textured phyllites, in which little trace of any clastic structure survives. Detrital granules of quartz and felspar may be seen, but biotite is wanting, though little patches of epidote perhaps represent it. "The base and main constituent of all these slates is a

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[1] For a description of various American clays see Merrill, *Guide to Collections in Applied Geol., Nonmetallic Minerals* (1901), 325–328, pl. 15–17.

[2] *G. M.* 1890, 264–273.

[3] Hutchings, *G. M.* 1896, 310.

[4] McMahon, *G. M.* 1890, 108–113; Hutchings, *ibid.* 188.

fine-grained mica, mostly lying flat in the plane of cleavage of the rock," and rutile-needles are usually abundant. The red and purple slates contain numerous scales of red micaceous hæmatite, probably representing the limonite of less altered deposits. A number of specimens of slates, Cambrian and Ordovician, from this region have been described by Mr Hutchings[1].

The Devonian slates of Cornwall (Tintagel, *etc.*) are described by the same author[2] as having suffered more alteration (ascribed to dynamic metamorphism) than the Welsh rocks. They have no clastic quartz, felspar, or biotite, and indeed some very small zircons seem to be the only derived constituents left unaltered. The main mass of the rock is of fine sericitic mica, the majority of the minute flakes being parallel to the cleavage of the rock. Minute needles of rutile are very abundant. Another very common mineral is micaceous ilmenite in flakes about ·002 inch in diameter. This is either opaque or transparent, with a deep brown colour, and sometimes encloses characteristic skeletons of rutile (sagenite). Other constituents of some of these slates are secondary quartz, calcite, chlorite, ottrelite, garnet, *etc.*

The Cambrian *phyllites* of the Ardenne have been carefully examined by Prof. Renard[3], who finds that the rocks have been completely reconstituted in place. The chief mineral is usually a colourless sericitic mica, its flakes having a general parallelism with the cleavage or schistosity of the rock. This and quartz usually constitute the principal part of the bulk, and a green chlorite is also abundant. Needles of rutile and often of tourmaline lie in general parallel to the cleavage. The violet phyllites have micaceous hæmatite ('oligiste'); in others micaceous ilmenite occurs, with interpositions of sagenite. Other minerals found in particular rocks are magnetite and pyrites, a manganese-garnet (spessartine) in minute crystals, ottrelite, zircon, carbonaceous matter, *etc.* The magnetite in the 'phyllade aimantifère' was formed before the cleavage of

[1] *Pr. Liverp. G. S.* (1900) viii, 464–471, pl. I, and (1901) ix, 113, 114, pl. VI, figs E, F.

[2] *G. M.* 1889, 214–220; 1890, 317–320.

[3] *G. M.* 1883, 322–324 (Abstract).

the rock, and is surrounded by the curious eyes of chlorite and quartz already referred to. The ottrelite was formed subsequently to the cleavage of the rocks which contain it, and its flakes do not lie parallel to the cleavage-planes.

American phyllites exhibiting all the salient characteristics have been described from the Piedmont Plateau in Maryland[1], from the Lisbon group in New Hampshire[2], and from Coanicut Island, R.I.[3] A fuller account, with coloured plates, has been given by Nelson Dale[4] of the phyllites of the slate-belt of New York and Vermont. These rocks consist of sericitic mica (about 40 *per cent.*), quartz, and chlorite, with carbonates, pyrites, sometimes hæmatite, zircon, and tourmaline, and in all cases minute needles of rutile.

Of ordinary slaty cleavage good illustrations are afforded by the Cambrian and Ordovician in North Wales, the Devonian in Cornwall, and some other British Palæozoic rocks. Some of these (Llanberis Slates) exhibit the deformation of originally spherical spots. Various kinds of 'eyes' about enclosed pyrites crystals may be seen at Penrhyn (fig. 55, *A*), Snowdon, Blaenau Ffestiniog, Whitesand Bay, *etc.*, and in the Cowal district of Argyllshire[5]. Special structures of the nature of *false cleavage* may be examined in the Skiddaw Slates of the Eden valley (Brownber, near Appleby, fig. 55, *B*), and of Snaefell in the Isle of Man, in the debatable rocks of the Start in South Devon[6] and in the remarkable 'gnarled' beds of Amlwch in Anglesey and of Aberdaron, *etc.*, in the west of Caernarvonshire. These last shew very beautifully all the characteristic structures of 'mountain-building,' on a small scale, and such rocks afford from this point of view an interesting study. Prof. Heim, in a figure[7] illustrating the passage of an overfold into an overfault by the obliteration of the 'middle

[1] G. H. Williams, *Bull. G. S. Amer.* (1891) ii, 305–307; Diller, 317–320.

[2] Diller, 321–323.

[3] Pirsson, *A. J. S.* (1893) xlvi, 376, 377.

[4] 19*th Ann. Rep. U. S. Geol. Sur.* (1899) part iii, 226–260, 265, 288–290, pl. xxxv–xxxix.

[5] Clough, *Mem. Geol. Sur. Scot., Geol. of Cowal* (1897), 57, 80.

[6] G. M. 1889, 214–220; 1890, 317–320.

[7] *Mechanismus der Gebirgsbildung* (1883), pl. xv, fig. 14.

limb,' gives for the scale '$\frac{200}{1}$ to $\frac{1}{10000}$ of natural size.' Perhaps the best British districts for studying the various forms of false cleavage are the Isle of Man, where the Skiddaw Slates exhibit a great variety of interesting structures, and the Cowal district of Argyllshire[1].

[1] Clough, *l.c.*, 7–29.

CHAPTER XVIII.

CALCAREOUS ROCKS.

The different kinds of limestones (Fr. calcaire, Ger. Kalkstein), consisting of carbonate of lime with various impurities or foreign materials, are almost all in great measure of organic origin. The hard parts of calcareous organisms are composed of calcite or aragonite[1], or both, with a small quantity of phosphate, *etc.* It will be seen that aragonite is always the unstable form of carbonate of lime, and tends to be converted into the stable form, calcite.

The impure calcareous rocks may include a considerable amount of non-calcareous material; either sand-grains (calcareous grit) or finer detritus (argillaceous limestone, marl) or volcanic *débris* (calcareous tuff).

With the limestones must be classed those rocks in which dolomite takes the place of calcite. These are called dolomite-rocks or dolomites, the name dolomitic limestone or magnesian limestone being more correctly applied to rocks in which both minerals are well represented. Many dolomitic rocks can be proved to have originated from ordinary limestones, the magnesia which replaced part of the lime having been derived from some external source.

We shall also briefly notice certain other rocks, such as some bedded iron-stones, which are genetically connected with the limestones, and some siliceous rocks of like origin.

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[1] According to Miss Kelly the substance which has been regarded as aragonite is in reality a third form of lime carbonate, which she names 'conchite'; *M. M.* (1900) xii, 363–370.

Much valuable information concerning limestones is con-tained in Dr Sorby's Presidential Address to the Geological Society[1], while British limestones from various horizons have been studied by several other observers[2].

Organic fragments. Most of the fragments of calcareous organisms that form part of rocks have something in their mineral nature, their structure, or their mode of preservation, that enables us to refer them to their proper order or class, or at least sub-kingdom.

Among vegetable organisms, the *calcareous algæ* figure largely in the deposits now forming round coral-islands[3] and to a less extent in some deep-sea deposits, while the equivalents of these rocks are recognized among the Tertiary and Recent strata in various parts of the world[4]; *e.g.* the Lithothamnion Limestone and Leitha Limestone of the Vienna basin (compare fig. 56). Calcareous algæ are concerned in the formation of some modern oolitic accumulations, and Girvanella, which figures largely in association with oolitic structure in rocks of various ages, is perhaps a vegetable organism; while the peculiar algous flora of hot springs is instrumental at the present day in producing certain deposits of travertine (Mammoth Hot Springs[5]). The part played by algæ in the formation of some of the older limestones, such as the Alpine Trias, seems to be of considerable importance[6]. In some fresh-water lime-

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[1] *Q. J. G. S.* (1879) xxxv, *Proc.* 56–95. On calcite and aragonite organisms, see also Cornish and Kendall, *G. M.* 1888, 66–73 ; Kendall, *Rep. Brit. Ass.* for 1896, 789–791.

[2] See especially several papers by Wethered, *Q. J. G. S.* (1888–1893) xliv–xlix, *etc.* ; Jukes-Browne and Hill on Chalk, *etc., ibid.* (1887–1889) xliii–xlv.

[3] See Murray and Renard, 'Challenger' Report on *Deep-Sea Deposits* (1891), pl. XIII, XIV.

[4] Murray, *Scott. Geog. Mag.* (1890) vi, pl. I (Malta) ; Hill, *Q. J. G. S.* (1891) xlvii, 243–248, pl. IX (Barbados) ; Lister (and Murray), *ibid.* 602, 603 (Tonga Is.) ; Gregory, *Q. J. G. S.* (1892) xlviii, 538–540 (Trinidad) ; Hinde, *Q. J. G. S.* (1893) xlix, 230, 231 (New Hebrides). For good figures shewing the structures of Lithothamnion and other calcareous algæ see Rothpletz in *Zeits. deuts. geol. Ges.* (1891) xliii, pl. XV–XVII.

[5] Weed in *9th Ann. Rep. U. S. Geol. Sur.* (1890) 642–645, *etc.*

[6] *Cf.* Seward, *Science Progress* (1894), ii, 10–26.

stones, such as those of Bembridge and of Purbeck[1], *Chara* is sometimes an important element.
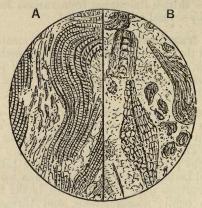
Fig. 56. Recent organic limestones, composed largely of calcareous algæ, Eua, Tonga Islands; × 20.

A is a characteristic section of *Lithothamnion* [1271]. *B* shews foraminifera and fragments of algæ in a recrystallized calcareous matrix [1269].

The tests of calcareous *foraminifera* commonly occur entire, and are readily recognized, though in some cases the chambers become detached (Globigerina, fig. 65). The material is calcite or aragonite in different forms (answering to the division into Vitrea and Porcellanea of some authors), and probably the latter have been largely destroyed in some older limestones. Foraminifera occur in many shallow-water limestones[2], and make up a large part of the so-called coral-limestones[3], besides forming the bulk of extensive deep-sea deposits. The Nummulitic Limestone is a well-known instance of a rock composed

[1] Wethered, *Pr. Cottesw. F. N. Club* (1891), x, 101, 102, with plate.

[2] See, *e.g.*, Guppy, *Tr. Roy. Soc. Edin.* (1885) xxxii, pl. cxlv, figs. 1, 4 (Solomon Is.); Jennings, *G. M.* 1888, pl. xiv (Orbitoidal Limestone of Borneo).

[3] See Guppy, *The Solomon Islands, Geology, etc.* (1887), 73–76; and *Tr. Roy. Soc. Edin.* (1885) xxxii, 545–581; Lister (and Murray), *Q. J. G. S.* (1891) xlvii, 602–604 (Tonga Is.).

largely of foraminifera. Other examples are the Alveolina, or Miliolite Limestone of Mixen Rocks near Selsea and the Saccamina Limestone of Northumberland.

The interior of a foraminiferal test may be filled in by crystalline calcite, often with such a radial arrangement of fibres as to give a very perfect black cross in each chamber when examined between crossed nicols. In many modern sediments[1] formed near a continental shore-line the chambers are occupied by a deposit of green *glauconite*, which, by the removal of the calcareous test, may be left in the form of casts; and this seems to be the usual mode of origin of glauconite-sands, such as are found at various geological horizons[2].

The true *corals* consist, according to Dr Sorby, of little fibres, or in some cases granules, of aragonite; but it appears that calcite enters into the composition of some forms. Mr Kendall states that, while almost all the reef-building forms have aragonite skeletons, all the deep-sea corals examined by him are of calcite. Of the Rugosa some consist largely of calcite fibres roughly parallel to the outlines of the several parts of the skeleton, while the mode of preservation of others seems to indicate that they were composed largely of aragonite. The so-called coral-rock, coral-sand, and coral-mud of Recent strata and of deposits now forming often consist largely of calcareous algæ or foraminiferal tests, but some are of almost pure corals and coral fragments. Among older rocks having this constitution may be mentioned parts of the Mountain Limestone and the Coral Oolite and certain Devonian limestones of South Devon (Torquay and Plymouth).

The hard parts of *echinoderms* have an unmistakable appearance. Each element (plate or joint) behaves optically as a single crystal of calcite, the larger ones shewing the characteristic cleavage. The organic nature is indicated only by the external form, internal canals, *etc.* Spines of echinoids,

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[1] Murray and Renard, *Deep-Sea Deposits* (1891), pl. xxiv, xxv.
[2] See, *e.g.*, Murray, *Scott. Geog. Mag.* (1890) vi, 464, 465, pl. ii, fig. 2 (Malta); Gregory, *Q. J. G. S.* (1892) xlviii, 540 (Trinidad). *Cf.* Sollas, *Q. J. G. S.* (1872) xxviii, 399 (Cambridge Greensand), and Hume, *ibid.* (1897) liii, 569–571 (U. G. S. of Woodburn, Antrim).

joints of the stems of crinoids, *etc.*, may be distinguished by their size and outline (fig. 57).
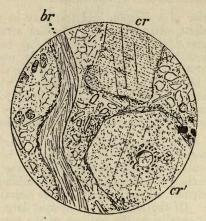
FIG. 57. LIASSIC LIMESTONE, SKYE ; × 15 :

shewing joints of crinoid stems (*Pentacrinus*) cut longitudinally (*cr*), and transversely (*cr'*), each consisting of a single crystal of calcite ; also part of a brachiopod shell (*Rhynchonella*, *br*), with its characteristic lamellar structure. The matrix is a recrystallized calcite mosaic enclosing numerous detrital grains of quartz and flakes of muscovite [1791].

The structure of the hard parts of *crustacea* is also fairly constant and quite different from the preceding. The shell is built of fibres of calcite set everywhere perpendicular to the surface, the optic axis of each fibre coinciding with its length. The general outline suffices to distinguish, *e.g.*, between entomostracan tests (abundant in many limestones) and fragments of trilobites (fig. 58, *A*).

Both calcite and aragonite enter into the composition of the *polyzoa*, and in some genera, according to Messrs Cornish and Kendall, the two occur in separate layers, the aragonite layer being in this case the outer one.

The shells of *brachiopods* are wholly of calcite, with a characteristic structure. "They are made up of laminæ, consisting

of flattened fibres or prisms, often passing along more or less parallel to one another over a considerable area, but mixed up
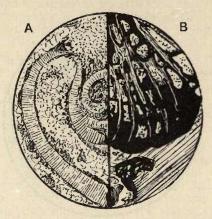
FIG. 58.   CARBONIFEROUS LIMESTONE, CLIFTON, BRISTOL; × 20.

A shews a portion of a trilobite with the characteristic structure of the crustacea [981]. *B* polyzoa replaced by opaque limonite, mixed with silica, in a matrix of coarsely crystalline calcite [972].

with other systems which cross them at various angles." These laminæ lie oblique to the surface of the shell, and the individual fibres do not give strictly straight extinction (fig. 57). The 'perforations' of some brachiopod shells can be seen, but they are not a characteristic feature.

The shells of *lamellibranchs* have more than one type of structure. In some ostreid genera (Ostrea, Pecten, Gryphæa, Inoceramus) the whole is of calcite in irregular flattened fibrous plates, producing a structure not unlike that of brachiopods. The shells, however, are usually of stouter build, and they tend to break up into their component prisms or fibres, which are often found detached, *e.g.*, Inoceramus in the Chalk.   On the other hand, most lamellibranch shells consist originally of aragonite, and are commonly preserved only as casts in calcite mosaic (fig. 59).   In some genera (Pinna, Mytilus, Spondylus)

there is, according to Dr Sorby, an inner layer of aragonite protected by an outer layer of calcite.
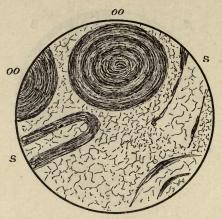
FIG. 59. OOLITIC LIMESTONE, MILLEPORE OOLITE, WHARRAM, EAST YORKSHIRE ; × 20 :

shewing oolitic grains (*oo*) and chips of lamellibranch shells (*s*) in a matrix which has recrystallized as a mosaic of clear calcite [1794].

Most *gasteropods* have shells wholly of aragonite, which is readily replaced by a mosaic of crystalline calcite. In a few cases, however, *e.g.* Scalaria, the whole is of calcite (Cornish and Kendall). Others have a layer of aragonite covered by a layer of calcite : either the former (Murex) or the latter (Purpura) may form the bulk of the shell.

Of the *cephalopoda*, the shells of Nautilus and the ammonites were originally of aragonite, but the aptychi of the ammonites were of calcite. The belemnites had the guard of calcite, with a characteristic radial arrangement of fibres about an axis, but the phragmocone was of aragonite.

The tests of *pteropoda* consist, according to Mr Kendall, of aragonite, and may sometimes be recognized by their form in sections. Exceptionally they form the main constituent of a limestone, and 'pteropod ooze' is one of the deep-sea deposits now forming in some parts of the ocean.

Oolitic structure[1]. Many shallow-water limestones, of all geological ages, contain little spheroidal grains built up of successive coats of calcareous material, and these may be so numerous as to make up the chief bulk of the rock. Such rocks are called oolitic limestones, oolites, or roestone (Ger. Rogenstein). For the coarser types, in which the grains may reach the size of peas, and are often of rather irregular or flattened form, the name pisolite (Ger. Erbsenstein) is used.

In addition to the concentric-shell arrangement, there is often a more or less evident radial structure in each grain, and closer examination shews that the minute elements which build up the successive layers are set in some cases radially, in other cases parallel to the layers.

As a result of either of these arrangements an oolitic grain, examined in section between crossed nicols, should give a black cross comparable with that observed in the spherulites of igneous rocks. Owing to the departure from true sphericity, the admixture of granular material not sharing the definite orientation described, and the effect of iron-staining and other secondary changes, an accurate black cross is not seen in every case.

The concentric layers have been formed upon a nucleus, which may be a chip of shell or other organic body, a quartz-granule, or merely a pellet of fine calcareous mud. Similar coatings are often to be seen upon fragments of shell, *etc.*, too large to be built up into round grains. Sometimes an oolitic grain has been broken and the separated fragments subsequently coated with fresh layers of calcareous deposit; or again two or three contiguous grains may be enveloped in one mantle and become a compound grain.

Oolitic grains differ as regards their material (calcite or aragonite), the orientation of their minute elements (radial or tangential), the presence or absence of finely granular calcare-

[1] On the oolitic structure and its significance see Sorby's *Presid. Address, l. c.*; also Teall in *Mem. Geol. Sur., Jurassic Rocks of Britain,* vol. iv, pp. 8–12, pl. I, II, 1894; Wethered (papers cited). Various types of oolitic grains are described and figured by Harris, *Pr. Geol. Ass.* (1895) xiv, 59–79, pl. III, IV.

ous matter without special orientation, or of impurities, and in other respects. One common type[1], exemplified in many British limestones, has well-marked concentric shells, each of which consists largely of minute calcite prisms or fibres set radially. There may or may not be an evident radial structure in the grain as seen in a thin slice. The black cross seen in polarized light is often imperfect or vaguely defined.

Another type is illustrated by the so-called Sprudelstein of the Carlsbad hot springs[2]. Here there are well-marked concentric shells but no radial structure. The material is aragonite and the minute elements are set mainly tangentially to the concentric layers. This gives a well-defined black cross. Dr Sorby found recent oolites from Bahama[3] and Bermuda to have a similar constitution, but with some unoriented granular material, and he observed the same in the Bembridge Limestone of the Isle of Wight.

It is impossible to say with certainty to what extent aragonite oolitic grains have once been represented in our older rocks. In numerous instances the present structure of the grains shews that they have been recrystallized. They often consist of crystalline calcite, either in a mosaic or in wedges with a rough radial arrangement. In some cases there is an eccentric radial structure, as if the recrystallization had started at one or more points on the circumference of the grains.

It is a somewhat difficult question how far the original structure of the different types of oolitic grains is due on the one hand to mechanical aggregation or on the other to crystallization, and it further appears that organic agency may often have played an important part. The Carlsbad Sprudelstein, the calcareous sand of Salt Lake, and other modern oolites seem to be connected with lime-secreting algæ; while Mr Wethered[4] finds the problematical organism Girvanella in

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[1] Cohen (3), pl. LXIII, figs. 2, 3.

[2] Harris, *l. c.*, pl. III, fig. 9.

[3] *Ibid.* figs. 6–8 and pp. 67–70.

[4] See papers cited below, but especially *Q. J. G. S.* (1895) li, 196–206, pl. VII, where the organic theory is extended to oolitic limestones in general: also *Proc. Cotteswold Nat. Field Club*, 1895–6.

many oolitic rocks of various ages. It is well seen encrusting the successive layers of large pisolitic grains in such a rock as the Pea Grit of Cheltenham, and again in some oolites, *e.g.* Wenlock Limestone (fig. 60).

FIG. 60. OOLITIC GRAIN FROM THE WENLOCK LIMESTONE, LONGHOPE ; × 6.

The concentric coats are built up largely of the interlacing tubes of *Girvanella*. [This figure was kindly furnished by Mr Wethered.]

Matrix of limestones. Recognizable fragments of organisms, together with oolitic grains, if present, may make up a variable part or even the chief bulk of a limestone. The remainder, in rocks which have suffered no important secondary changes, consists of a calcareous mud in which the fragments (and oolitic grains) are embedded. This finely divided material is mostly carbonate of lime, and must be in great measure derived from the attrition and disintegration of calcareous organisms, though chemical deposition may perhaps play some part, and material may be furnished by the degradation of older limestones. Iron-compounds often occur as an impurity, producing a yellow or brown stain by oxidation. Fine sand of detrital origin is often present in shallow-water limestones, and may be abundant (calcareous grits). Similarly, an admixture of argillaceous matter gives rise to argillaceous limestones and calcareous marls, or by the presence of volcanic detritus

and ashes the rock becomes a calcareous tuff. In some argillaceous limestones, such as those of the English Lias, it is probable that much even of the calcareous matter is of detrital origin[1].

In many limestones, and especially those belonging to the older formations, the original finely divided calcareous matter has been partially or wholly *recrystallized* into a granular calcite-mosaic of fine or sometimes comparatively coarse texture. Crystalline limestones or marbles are thus formed without any special conditions of the kind usually implied in the term metamorphism. The recrystallization seems to originate at certain points in the mass and spread. The process has a purifying effect, and ferruginous impurities often appear as if pushed before it to collect in particular patches. The recrystallized carbonate of lime is always calcite, aragonite being converted in the process to the stabler form. In such a crystalline matrix casts after aragonite shells may usually be recognized by a rather coarser mosaic and by a thin film of impurities marking the original outline, even when they are not coated in oolitic fashion (fig. 59).

The recrystallized calcite usually forms a more or less finely granular mosaic in the interstices between the organic fragments, oolitic grains, *etc.* In some cases, however, the individual crystal-grains of calcite are of large size, so as to enclose numerous oolitic granules, shell-fragments, *etc.*, thus giving a structure like the ophitic and poecilitic in some igneous rocks. This has been remarked by Mr Teall in some of the oolitic building-stones of the Lincolnshire Limestone (Barnack, Ketton, Ancaster). An analogous structure has already been noted above in certain calcareous grits with abundant calcite matrix, the Fontainebleau Sandstone affording an extreme example.

In certain coarse-textured marbles the new-formed calcite occurs partly as a crystal outgrowth of fragments of crinoids, *etc.*, comparable with the quartz-cement of many quartzites (Clifton).

[1] Woodward, *Jurassic Rocks Engl. and Wales*, vol. iii (1893), 27–32 ; *cf.* Sollas, *Q. J. G. S.* (1879) xxxv, 492 (limestones in O. R. S. of Cardiff district) and *G. M.* 1900, 248–250.

In some oolitic limestones the original matrix has been in great measure removed by solution, leaving vacant spaces between the oolitic grains. This is seen in some of the Ancaster and Ketton building-stones, belonging to the Lincolnshire Limestone[1]. In other cases the oolitic grains are themselves recrystallized to a granular mosaic[2].

The quartz-sand, *etc.*, occurring as impurities in many limestones can be easily isolated by dissolving the rock in dilute acid, and sometimes present points of interest[3]. Minute perfect crystals of quartz may occur, sometimes evidently formed by secondary outgrowth from detrital quartz-grains (Clifton).

Deep-sea calcareous deposits. Beyond the broad belt of deposits now forming along the continental coast-lines and deriving their material in some degree from the waste of the land and from shallow-water organisms, and apart too from the special accumulations forming round coral- and volcanic islands, extensive calcareous deposits are found covering large areas of the floor of the deep ocean down to about 2800 fathoms. The most widely spread of these deposits is *globigerina-ooze*, consisting largely of the tests of Globigerina and other foraminifera[4], together with a smaller proportion of other organisms, such as siliceous radiolaria, and some non-calcareous matter of volcanic origin. Associated with the foraminiferal remains are immense numbers of very minute elliptic disc-shaped bodies, to which Prof. Huxley gave the name *coccoliths*[5]. These calcareous discs have been detached from the surface of certain globular organisms named coccospheres, referred to the algæ. The coccoliths have a diameter of ·0002 to ·0005

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[1] On this and some other north-country Jurassic limestones see *Naturalist*, 1890, 300–304.

[2] Cohen (3), pl. LXXIII, fig. 4.

[3] Wethered (Carboniferous), *Q. J. G. S.* (1888) xliv, 186–198 ; (Inferior Oolite) *ibid.* (1891) xlvii, 559–569.

[4] Murray and Renard, *Deep-Sea Deposits* (1891), pl. XI, figs. 1, 5, 6 ; XII ; XV, fig. 2.

[5] *Ibid.*, pl. XI, figs. 3, 4. See also Wallich, *Ann. Mag. Nat. Hist.* (1861) ser. 3, viii, 52–56, and on the coccoliths of the Chalk see Sorby, *ibid.*, 193–200.

inch. Associated with them are often other minute bodies in the form of slender rods with a crutch-like termination (rhabdoliths). Coccoliths and rhabdoliths are very characteristic of the deep-sea calcareous deposits, though not confined to them.

The inorganic residue of these rocks is essentially of volcanic material in a state of extremely fine division, and corresponds with the 'red clay' already noticed.

Various foraminiferal and other limestones have been described among Tertiary and Recent strata which approximate, in some cases very closely, to the essential characters of true deep-sea deposits[1].

Metasomatic changes in limestones. In many rocks which may be assumed to have been once ordinary limestones, the carbonate of lime has been partly, or even wholly, replaced by other substances, thus producing a change in the chemical composition of the rock (metasomatism). The most common of such changes is that in which calcite is converted into dolomite by the replacement of half its lime by magnesia (*dolomitization*). It seems to be clearly established that calcite and dolomite are not chemically isomorphous substances, but each has its own definite composition. The molecular ratio $CaO : MgO$ in dolomite is always unity, and a higher ratio in the bulk-analysis of a dolomitic rock indicates a mixture of dolomite and calcite.

In the finely granular mosaic which such rocks often present it may be difficult to distinguish the two minerals from one another without chemical tests[2]. One criterion is the much stronger tendency of dolomite to develope crystal outlines[3], always those of the primitive rhombohedron (fig. 61). In coarse-grained rocks the more marked cleavage-traces of calcite and the frequency in it of lamellar twinning[4] help to

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[1] *E.g.* Hill, *Q. J. G. S.* (1892) xlviii, 179 (Barbados).

[2] Lemberg has given a microchemical test applicable to rock-slices; *M. M.* (1889) viii, 166 (*Abstr.*).

[3] *Cf.* Wethered, *Q. J. G. S.* (1892) xlviii, fig. on p. 381 ; Rutley, *ibid.* (1894) l, pl. xix, figs. 5, 6.

[4] Cohen (3), pl. xxvii, fig. 4 (Carrara marble).

distinguish it from dolomite. Again, calcite is colourless in slices, while dolomite usually (but not always) has a yellow or
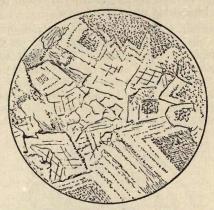
Fig. 61. Dolomitized limestone in Upper Coniston Limestone, Shap Wells, Westmorland; × 20,

The dolomite is here in good rhombohedra with a zonary structure marked by inclusions : some calcite remains as a clear mosaic [1616].

yellowish-brown tint. This coloration is probably due to iron. It may be remarked that another mineral of the same group is sometimes met with, *viz.*—chalybite, or siderite, the ferrous carbonate. This often builds little rhombs with curved outlines. It is of a somewhat deeper brown tint than dolomite, and in many cases encloses little opaque specks or minute crystals of pyrites.

Good examples of more or less perfectly dolomitized rocks occur in the Durness Limestones of Sutherland, the Bala and Coniston Limestones, the Devonian of Devonshire, the Carboniferous Limestone of many parts of England and Ireland, and the Permian Magnesian Limestone. Among foreign formations may be mentioned the Alpine Trias, dolomitic rocks attaining a great development in the southern Tirol.

In many cases the rocks give evidence of shrinkage during the process of dolomitization. There are often crevices and

cavities, which, however, may be filled subsequently by an infiltration of calcite. Some dolomitized oolitic limestones shew a little cavity in the centre of each oolitic grain (Magnesian Limestone near Hartlepool).

Again, certain *ironstones* have evidently been formed[1] by metasomatic changes from limestones. The process consists first in the replacement of calcite by ferrous carbonate (chalybite), and further, in many cases, in an oxidation of the latter, giving rise to magnetite, hæmatite, or limonite. The oolitic limestones seem to be specially liable to this kind of alteration, and the oolitic grains themselves shew the most advanced stage, the outer part of each grain being converted into mag-
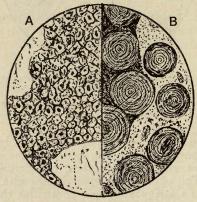
FIG. 62. IRONSTONES.

A. Ironstone-band in Scarborough Limestone, Scarborough; × 100, shewing an aggregate of minute rhombs of chalybite, often enclosing nuclei of pyrites. The clear grains, of which two are shewn, are quartz [946]. *B.* Oolitic ironstone, Claxby, Lincolnshire; × 20. Here the oolitic grains are transformed to limonite; the matrix is mostly of chalybite, but has undergone in patches the further change to limonite [1591].

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[1] See Sorby, *l.c.* pp. 54, 55; Judd, *Geol. of Rutland*, 117–138; Hudleston, *Pr. Geol. Ass.* (1889) xi, 117–127; Cole and Jennings, *Q. J. G. S.* (1889) xlv, 426, 427; Teall in *Mem. Geol. Sur., Jurassic Rocks of Britain*, vol. iii, p. 302; vol. iv, pl. ii, *etc.*

netite or limonite, while the matrix of the rock remains as chalybite or in part calcite. The chalybite matrix is fine-textured, and the mineral often shews imperfect crystal form, each crystal sometimes enclosing a nucleus of decomposing pyrites (fig. 62, *A*). In a more advanced stage of change patches of limonite replace the chalybite of the matrix (fig. 62, *B*), and even calcite shells of Pecten, *etc.*, are converted into hæmatite or limonite (*e.g.* the Dogger of the Peak in Yorkshire). The oxidation does not take place in the more argillaceous iron-stones, the iron remaining there in the form of carbonate. Valuable oolitic ironstones are worked in this country. That of Rosedale (Dogger) is magnetite, the Cleveland Main Seam[1] (Middle Lias) shews various stages of transformation and various admixtures of earthy matter, the Jurassic ores of Northampton and Rutland have specially the limonite type of alteration, and the Neocomian ores of Tealby and Claxby in Lincolnshire are similar. An oolitic ironstone with more gritty impurities occurs at Abbotsbury and Westbury in the Corallian group of the Isle of Purbeck[2].

The best known bedded ironstone of this kind in America is the Clinton ore, which occurs in the Silurian of the eastern states, and is worked at Clinton, N.Y., Birmingham, Ala., and elsewhere. Some beds are truly oolitic, while others have a quasi-oolitic appearance, the grains being rolled fragments of polyzoans replaced by iron-oxide. While some difference of opinion exists as regards the origin of the ore, it seems probable that it is, at least in great part, formed from limestone[3].

If the grains of an oolitic iron-ore be dissolved by acid, each leaves a shell or skeleton of silica soluble in caustic potash. This silica must have been introduced at some stage of the alteration of the original limestone. A similar siliceous skeleton is sometimes found in the grains of oolitic limestones where

[1] For figures of this and other oolitic ironstones see *Mem. Geol. Sur.*, *Jurassic Rocks*, vol. iv, pl. ii.

[2] Strahan, *Mem. Geol. Sur.*, *Geol. I. Purb.* (1898) 39; Teall in *Mem. Geol. Sur.*, *Jurassic Rocks*, vol. v (1895), 324; see also vol. iv, pl. ii, fig. 12.

[3] See Foerste, *A. J. S.* (1891) xli, 28, 29; Kimball, *Amer. Geol.* (1891) viii, 356, 357; Smyth, *A. J. S.* (1892) xliii, 487–496; Diller, 138–140.

no ferruginous replacement has taken place, or, again, silica may more or less replace the calcareous matter between the grains[1]. Although *silicification* is perhaps less common than some of the other metasomatic changes noticed above, it is found in numerous limestones of various ages. Sometimes the replacement of carbonate of lime by silica is confined to the organic remains, but in other cases it affects the whole body of the rock (*e.g.* some cherts). Parts of the Carboniferous limestones of Clifton shew examples of oolitic grains and organic fragments replaced by a mixture of limonite and silica. Good examples of cherts formed by the silicification of limestone (matrix and fossils alike) are found in the Portland Beds of the South of England.

An almost purely siliceous rock from eastern Pennsylvania[2] shews a beautiful oolitic structure, each little sphere, about ·04 inch in diameter, consisting of numerous concentric coats surrounding a nucleus, and the interspaces being also occupied by silica. Here there must evidently have been a molecular replacement of carbonate of lime by silica, and indeed associated rocks shew various stages of partial replacement. Some cherts in the Durness Limestone of Sutherland tell the same story, the oolitic structure being still discernible (Stonechrubie near Ichnadamff). Similar oolitic cherts occur in the Corallian of Yorkshire, in the Portlandian of St Alban's Head[3], and in the Carboniferous of South Wales[4].

Still another metasomatic change met with in some calcareous rocks is *phosphatization*. This usually affects some or all of the organic remains, or phosphatic nodules are formed having fossils of various kinds as nuclei. The phosphate of lime is presumably itself derived from organic bodies, but it is not clear to what extent it has been supplied contemporaneously with the deposit which contains the nodules. Deposits rich in phosphate occur at various horizons in the formations of this

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[1] Chapman, *G. M.* 1893, 100–104 (Devonian, Ilfracombe).

[2] Barbour and Torrey, *A. J. S.* (1890) xl, 247–249, with figures. Similar rocks occur at several localities in Missouri; Hovey, *ibid.* (1894) xlviii, 404, 405 ; Harris, *Pr. Geol. Ass.* (1895) xiv, 78, pl. IV, fig. 9.

[3] Teall, *Mem. Geol. Sur., Geol. I. Purbeck* (1898), 63, and *Jurassic Rocks*, vol. v (1895), 186.

[4] Watts, *Mem. Geol. Sur., S. Wales Coalfield*, part II (1900), 36.

country : the Cambridge Greensand may be taken as an example, where the fossils are largely phosphatized and also serve to some extent as the nuclei of nodules. In other instances phosphate of lime occurs as casts of foraminifera[1] or as grains more or less definitely replacing those bodies[2]. Phosphatic deposits are now forming in the ocean, both within the littoral belt and in connection with the globigerina-ooze, *etc.*[3]

Some British limestones[4]. After what has been said in the foregoing paragraphs, a few remarks on some of the more important calcareous formations of this country will be sufficient to illustrate our subject.

The Cambrian limestones of Durness, Assynt, and Skye are remarkably free from detrital impurities. They are in great part dolomitized, presenting a saccharoid texture.

The Bala-Limestone of North Wales is sometimes a fine calcareous mud-stone, sometimes recrystallized. The most conspicuous organic fragments are those of crinoids, which are in places very abundant, and polyzoa are also found. The Hirnant Limestone[5] has a peculiar type of oolitic structure, the grains having a chalcedonic skeleton and concentric zones rendered opaque by finely divided carbon. The Coniston Limestone of Westmorland is in its purer parts usually recrystallized throughout to a granular mass, in which the original characters are lost. In places it is dolomitized[6] (fig. 61). In its lower part it contains much non-calcareous material, chiefly volcanic, and at one horizon there is a breccia in which the enclosed fragments are of rhyolite, andesite, *etc.*, the matrix being calcareous[7]. At Keisley, in the Eden Valley district, the rock is in parts coarsely crystalline, so that, while the

[1] Chapman, *Q. J. G. S.* (1892) xlviii, 514–518, pl. xv (Chalk, Taplow).
[2] Strahan, *Q. J. G. S.* (1891) xlvii, 357–362 (Chalk, Taplow) ; (1896) lii, 465 (Lewes).
[3] Murray and Renard, '*Challenger' Report, Deep-Sea Deposits* (1891), pl. xx.
[4] Of American limestones a number of typical examples are described by Diller, *Educ. Ser. Rocks*, 102–132.
[5] Fulcher, *G. M.* 1892, 114–117, pl. iv ; Harris, *Pr. Geol. Ass.* (1895) xiv, 78, pl. iv, fig. 10.
[6] *Q. J. G. S.* (1893) xlix, 367.
[7] *Q. J. G. S.* (1891) xlvii, 309, 310.

outlines of the larger fossils are preserved, all minute structures are destroyed. At a lower horizon in the same district occur bands composed wholly of the little crustacean Beyrichia.

The Wenlock Limestone of Dudley, with a recrystallized matrix, still preserves abundant organic fragments, especially those of crinoids, entomostracans, trilobites, corals, polyzoans, and brachiopods. It sometimes has as much as 30 *per cent.* of foreign detrital material. At Malvern the rock is largely oolitic, the grains being set in a recrystallized matrix, and sometimes themselves recrystallized (the Wych). Composite and broken oolitic grains also occur (Croft). The Aymestry Limestone, from Dr Sorby's description[1], is very like the Wenlock.

Dr Sorby[2] has pointed out many interesting features in the Devonian limestones of Devonshire. The recognizable organic fragments are chiefly of crinoids and corals, and the finely divided calcareous matter is probably derived from the degradation of coral skeletons. This fine material has often been recrystallized in the usual fashion, the impurities being segregated into patches of finer texture. Again, rhombohedral crystals of dolomite (often ferriferous) have frequently been formed in the rocks[3], and some have become true dolomite-rocks, while a little pyrites, partly oxidized, is not uncommon. Many of the rocks shew slaty cleavage in every respect similar to that noticed in argillaceous strata.

The Carboniferous limestones of Clifton, Bristol, are largely built of recognizable organic fragments. Crinoids and sometimes ostracods are especially abundant in the Lower Limestones, foraminifera and the problematical organism Calcisphera in the Middle[4]. Numerous oolitic beds occur, and in some of

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[1] *L.c.* p. 60.

[2] *Phil. Mag.* (1856) ser. 4, 20–37. See also Wethered, *Q. J. G. S.* (1892) xlviii, 377–387, pl. ix.

[3] Wethered, *l.c.*, fig. on p. 381. On the partial silicification of some beds see Chapman, *G. M.* 1893, 100–104.

[4] Wethered, *G. M.* 1899, 78, 79, and *Rep. Brit. Ass.* for 1898, 862, 863 ; see also *G. M.* 1886, 529–540, pl. xiv, xvi (Forest of Dean), and Morton's *Geol. of Liverpool* (2nd ed., 1891), 25–27 (Flintshire). The microscopic characters of some Carboniferous limestones from North Wales and from Somerset are described by Beasley, *Pr. Liverp. G. S.* (1879) iii, 359–361.

these Mr Wethered[1] has found the oolitic structure to be connected with the growth of Girvanella. In others the oolitic grains are in some measure replaced by iron-oxides and silica, and some of the organic fragments (especially of polyzoa) also shew a ferruginous replacement (fig. 58, *B*). The interstitial calcareous mud is usually recrystallized as a rather coarse calcite-mosaic, and dolomitization occurs at some horizons.

The Mountain Limestone of the North of England is on the whole of similar character. The most frequent of the recognizable organic fragments are in many cases those of crinoids, and at some horizons in Derbyshire and Yorkshire these constitute the main bulk of the rock, but fragments of brachiopods, corals, polyzoa, and algæ also occur, and may be abundant, while foraminifera are often very plentiful[2]. Dr Sorby has pointed out that in Derbyshire some of the beds are pure dolomite-rocks[3].

Dolomite-rocks and dolomitic limestones occur at many localities in the Carboniferous of South Wales[4] and of Ireland[5]. They are in general highly crystalline, and all trace of organic structures is obliterated. A common type seems to be that in which the predominant dolomite, in more or less imperfect crystals, is cemented by calcite. This becomes evident on weathering, when the removal of the calcite sets the dolomite crystals free. The rocks are always more or less cellular or porous, but the cavities are commonly filled, or lined in drusy fashion, by calcite. Like phenomena occur in the Carboniferous limestones of the Isle of Man, and are beautifully exhibited on the shore at Castletown and Poolvash. The resulting dolomite-rock is often quite coarsely crystalline.

The Permian Magnesian Limestone is in general a true dolomite-rock, and in most cases all minute original structures

[1] *Q. J. G. S.* (1890) xlvi, 270–274, pl. xi: *cf.* Harris, *Pr. Geol. Ass.* (1895) xiv, 76, 77, pl. iv, figs. 7, 8.

[2] The Saccamina Limestone of Northumberland is an example of a Carboniferous rock composed essentially of foraminifera.

[3] See also Rutley, *Q. J. G. S.* (1894) l, 381, 382, pl. xix, figs. 5, 6.

[4] Watts, *Mem. Geol. Sur., S. Wales Coalfield*, part ii (1900), 34–36, pl. i.

[5] Hardman, *Pr. Roy. Ir. Acad.* (1876) ser. 2, ii, 723–726.

have been lost in the changes which converted the rock to a granular mass of dolomite. When organic fragments are recognizable they are most frequently those of shells and polyzoa. Locally in South Yorkshire the latter bodies make up almost the whole of the rock (Brodsworth, Cadeby, *etc.*). Near Abergele in North Wales foraminifera and corals form a large part. Dr Sorby describes the Magnesian Limestone north of Nottingham as comparatively coarse-textured, with evident rhombohedral crystals. The usual type in Durham is often fine-grained, the elements being of irregular form. Sometimes an interlocking arrangement of the granules, aided by the presence of little vacant spaces, gives a certain flexibility to the rock[1] (Marsden). The little cavities or pores are, however, as in other dolomitic rocks, often occupied by crystalline calcite. The well-known nodules of Marsden and Sunderland, several inches in diameter and with well-marked radial crystallization, are of calcite with but little carbonate of magnesia[2]. The Magnesian Limestone is, as a rule, tolerably free from foreign detrital matter, but locally it becomes arenaceous. Dolomitic sandstones occur near Mansfield, and the attenuated representative of the Magnesian Limestone in Westmorland is full of angular quartz-grains.

In the lower Oolites of the Cotteswold and Bath districts[3] fragments of shells, crinoids, and polyzoa, tests of foraminifera and other organic remains are recognized in variable proportions. Most of these limestones are oolitic, but the original structure of the oolitic grains is often destroyed by recrystallization. In the best preserved examples Girvanella is detected at various horizons, and it is specially well exhibited in the coarse pisolite known as the 'Pea Grit[4].' The rocks contain various small proportions of insoluble residue consisting of detrital mineral fragments (quartz, *etc.*).

The Lincolnshire Limestone and Millepore Oolite of the

[1] Card, *G. M.* 1892, 117–124.

[2] Garwood, *G. M.* 1891, 434–440.

[3] Wethered, *Q. J. G. S.* (1890) xlvi, 274–277, pl. xi; (1891) xlvii, 550–569, pl. xx; *Pr. Cottesw. F. N. Club* (1892), x, 119, 120; Harris, *Pr. Geol. Ass.* (1895) xiv, 70–72, 75, 76; pl. iv, figs. 1, 2, 6.

[4] See also *G. M.* 1889, 197, 198, pl. vi.

North of England[1] are made up largely of oolitic grains of the ordinary type, consisting of a nucleus of a shell-fragment, a quartz-grain, or a brown pellet of mud, surrounded by numerous iron-stained coats, in which a radial structure is sometimes discernible. The organic fragments include chips of brachiopods and Pecten, recrystallized fragments of aragonite shells, foraminifera, valves of ostracods, pieces of echinoderms, etc., in different beds: e.g. abundant brachiopod spines in the Rhynchonella spinosa beds. The general matrix of fine calcareous mud is almost always converted into a crystalline calcite-mosaic with localisation of the ferruginous impurities, and most of the rocks contain a considerable amount of angular quartz-sand. This last feature is more prominent in the Scarborough Limestone and the Cornbrash. The former, especially in certain nodular bands, is often an iron-stone consisting of minute rhombohedra of chalybite, with no calcite remaining except in the fragments of shells.

The Coral Oolite of Malton is another good specimen of an oolitic limestone with recrystallized matrix. Besides foraminifera, crinoid fragments, etc., it contains abundant remains of aragonite gasteropods replaced by calcite mosaic. The oolitic grains are sometimes large enough to be termed pisolitic, but the Girvanella noticed by Mr Wethered[2] in the Osmington pisolite, near Weymouth, is not yet recorded from Yorkshire. The last-named author (l.c.) has described the Portland rocks[3] with their recrystallized oolitic grains. The silicification of some beds in that district has already been referred to.

The microscopic characters of the English Chalk have been described by Dr Sorby[4], Messrs W. Hill and Jukes-Browne[5],

[1] Naturalist, 1890, 300–304. For figures of various Lower Oolitic limestones see Mem. Geol. Sur., Jurassic Rocks, vol. iv, pl. i.

[2] G. M. 1889, 197, pl. vi, fig. 9; Q. J. G. S. (1890) xlvi, 277–279, pl. xi, figs. 6–8.

[3] On the Portland Oolite see also Harris, Pr. Geol. Ass. (1895) xiv, 72–74, pl. iv, figs. 3, 4; Teall, Mem. Geol. Sur., Jurassic Rocks, vol. v (1895), 186.

[4] Q. J. G. S. (1879) xxxv, Proc. 48, 49.

[5] Q. J. G. S. (1886–9) xlii, 228–230, Cambridge and Hertfordshire; 242, 243, Dover; xliii, 580–585, W. Suffolk and Norfolk; xliv, 355–357, Lincolnshire and Yorkshire; xlv, 406–413, Berkshire and Wiltshire; see

and others. The tests of foraminifera, and especially detached cells of Globigerina, are abundant in many examples, though they rarely form the chief constituent of the rock. The cells are empty in the soft chalk of the South, but filled with calcite in the hard chalk of Yorkshire. Radiolarian remains have been preserved only exceptionally[1]. Molluscan fragments, and especially the detached shell-prisms of Inoceramus, are often well represented: in the Totternhoe Stone shell-fragments form 60 to 70 per cent. of the rock. In most cases, however, the great bulk of the rock consists of very finely divided calcareous material, the nature of which can be studied only by rubbing the chalk with water and examining the powder. Coccoliths abound in this fine mud[2], but the minute granules are mostly such as would come from the destruction and dissolution of aragonite shells, corals, etc. Foreign detrital matter is rare in the Chalk, except at certain horizons, but is abundant in the Red Chalk of Hunstanton, Lincolnshire, and Yorkshire[3]. The Cambridge Greensand has rather large quartz-grains, with some mica. It also contains a considerable number of glauconite grains, usually as perfect internal casts of foraminifera[4], and glauconite occurs at some higher horizons in smaller quantity. Sponge-spicules may be found in some examples. Those in the Lower Chalk of Berkshire and Wiltshire are sometimes preserved in the original colloid silica, sometimes replaced by calcite, while little globules of colloid silica (·0006 inch in diameter) occur in the rock.

also Hume, *Chem. and Micro-miner. Researches on the Up. Cret. Zones of the S. of Engl.* 1893, and on the Chalk of Antrim, *Q. J. G. S.* (1897) liii, 568–584. For a general summary of the microscopic characters of the English Chalk see Jukes-Browne, *Pr. Yorks. Geol. Pol. Soc.* (1895) xii, 385–395.

[1] Hill and Jukes-Browne, *Q. J. G. S.* (1895) li, 600–603 (Melbourn rock).

[2] On coccoliths in the Chalk see Sorby, *Ann. Mag. Nat. Hist.* (1861) ser. 3, viii, 193–200.

[3] On the mineral constitution of the Red Chalk and its insoluble residue see *Mem. Geol. Sur., Cret. Rocks*, vol. i (1900), 345, 346.

[4] Sollas, *Q. J. G. S.* (1872) xxviii, 399.

CHAPTER XIX.

PYROCLASTIC ROCKS.

THE fragmental volcanic rocks are in general the products of explosive action[1]. The ejected material varies from the finest dust to pieces several inches, or even feet, in diameter, but the coarsest types do not require special notice here.

What is known as *volcanic dust* or fine ash is no doubt partly due to the comminution of rocks and crystals by friction during the explosion, but a great part of it must represent lava blown out from the vent in liquid form and solidified almost instantaneously in the air. It doubtless solidifies as glass, but may, of course, be subsequently devitrified. The bodies known as volcanic *bombs* and *lapilli* are of very various sizes. They may have spheroidal or more peculiar forms; or again they may be irregularly shaped or fitted together. Some kind of concentric structure, with a nucleus and an outer crust, is often seen, or the exterior may be scoriaceous. In many volcanic accumulations *crystals* play an important part. They are commonly idiomorphic, though frequently broken, and belong to the minerals common in lavas. They may sometimes be torn from solid rocks, but more generally they must have been contained in a fluid matrix before the eruption. We also find *rock fragments*, either angular or, in submarine deposits, partly rolled and worn. They are commonly of lava for the

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[1] The exceptions ('flow-breccias,' *etc.*) are not important for our present purpose.

most part, shattered and blown out by the explosion, but we also find pieces of igneous rocks which must have come from greater depths, or fragments of slate, grit, limestone, *etc.*, representing strata broken through, and often shewing evident metamorphism. The larger 'ejected blocks' are frequently of these foreign and non-volcanic rocks.

The rocks formed by the accumulation of these various materials have received many names. The term *ash*, applied to the finer incoherent products of modern volcanoes, is sometimes used in a more extended sense; but the older, more or less compacted, deposits of ash-material are usually called *tuffs*. A large proportion of them were evidently laid down under water: subaërial accumulations have less frequently been preserved from destruction. Rosenbusch, in describing the ancient acid tuffs, divides them into compact tuffs, crystal-tuffs, and agglomeratic tuffs, and the division may be applied to rocks of other composition; but, since the relative proportions of dust, crystals, and lapilli, *etc.*, may vary to any extent, no precise divisional lines can be drawn. If angular rock-fragments be largely represented, the deposit is termed a *volcanic breccia*, or if the fragments be rounded, a *volcanic conglomerate*.

According to the nature of the material, the rocks may often be spoken of as 'rhyolite-tuff,' 'trachyte-tuff,' *etc.*, or, again, 'andesite-breccia,' 'trachyte-conglomerate,' and so forth; but, owing to the admixture of various materials, the rocks do not always correspond exactly even with contemporaneous lavas directly associated with them.

Further, when deposited under water, the volcanic material may become mixed with ordinary detritus or with calcareous matter, and so we have earthy tuffs, calcareous tuffs, *etc.*, some of which are fossiliferous.

General characters. Fragmental volcanic rocks have received much less minute study than lavas, and indeed present greater difficulty, requiring for the finer material the use of high magnifying powers.

Typical volcanic dust in a fresh state seems to consist essentially of glass-particles, with only a minor proportion of comminuted crystals and microlites. The glass-fragments

have a peculiar structure and a characteristic form. This is due to the immense number of contained steam-bubbles, which are drawn out into minute tubes, causing the glass to break into linear shapes with a longitudinal striation. The glass is distinguished from comminuted felspar by the absence of true rectilineal boundaries and the isotropic character. The minute fragments are colourless, except in the case of basic glasses, which may be of a brown tint. According to Murray and Renard[1], the characteristic appearance of these glass fragments may be recognized even in excessively small particles (less than ·0002 inch), while the distinctive properties of most minerals cannot be detected in fragments of smaller dimensions than ·002 inch. The minerals commonly recognized are the familiar constituents of volcanic rocks—especially plagioclase, pyroxenes, and magnetite[2], for many of these very fine volcanic dusts are of the nature of pyroxene-andesite. The crystals are often coated with glass or have glass adherent.

FIG. 63. BASIC TUFF, ORDOVICIAN, WET SLEDDALE NEAR SHAP; ×20.

The bulk of the rock is of very fine particles, but encloses some rock-fragments and numerous crystals of felspar, which tend to stand perpendicularly to the lamination of the matrix [895].

[1] See especially *Nature* (1884), xxix, 585–589.
[2] Fouqué and Michel Lévy, pl. xiii, fig. 4.

The authors named find precisely similar material to be widely distributed in modern deep-sea deposits, where it accumulates from the fall of wind-borne dust and the disintegration of floating pumice.

In tuffs formed not far from a volcanic centre, crystals of recognizable size, perfect or broken, are often embedded in a fine-textured matrix. These frequently shew a characteristic arrangement, standing with their long axes vertical or roughly perpendicular to the lamination of the matrix, as if dropped into their place from above (fig. 63).

In any except comparatively young tuffs the original character of the finely divided material is largely obscured by secondary changes, the loose texture of the deposits rendering them peculiarly liable to alteration. According to the nature of the rock, such minerals as quartz, sericitic mica, chlorite, calcite, etc., are developed at the expense of the original dust. Silicification is very common in the acid tuffs. Fragments of lava naturally suffer less than the enclosing matrix, but if glassy they readily become altered. In particular the more basic glasses, such as basalt and augite-andesite, are hydrated and converted into the transparent brown or yellow, or more rarely green, substance known as palagonite[1].

In some cases it is very difficult to distinguish compact rhyolite-tuffs, silicified or otherwise altered, from rhyolites which have undergone similar changes, the lamination of the one and the flow-structure of the other often increasing the resemblance. When enclosed crystals occur, their characteristic orientation, as noted above, will often furnish a clue; or again the occurrence of fragments with concave outlines[2] (Ger. Bogenstructur) is sufficiently suggestive (fig. 64, A). Old tuffs of andesitic or basaltic composition, when more or less cleaved and impregnated with secondary chlorite, calcite, and other substances, may sometimes be mistaken for crushed lavas of like composition, or vice versâ, unless distinct fragments, such

[1] For some discussion of the nature of this substance, see Zirkel, *Micro. Petr. Fortieth Parallel*, pp. 273–275 (1876). The basic glass which has not suffered hydration is sometimes termed sideromelane: see also Murray and Renard, *Chall. Rep.*, *Deep-Sea Deposits* (1891).

[2] Rutley, *Q. J. G. S.* (1902) lviii, p. 30, fig. (Builth).

as lapilli, can be detected. These lapilli can often be recognized by a rounded outline, or a vesicular structure, or an opacity due to finely divided magnetite[1].

It will easily be understood that fine-textured tuffs may exhibit precisely the same phenomena of slaty cleavage as those seen in argillaceous sediments, while the coarser pyroclastic rocks (volcanic breccias and agglomerates) are more readily crushed than solid rocks such as lavas.

Illustrative examples. Without attempting to deal systematically with the great variety of tuffs, agglomerates, *etc.*, it will be sufficient to draw attention to a few, which have been already described, and illustrate various points of interest. As typical of many fine *volcanic dusts*, we take that which was spread over a vast extent of country after the great eruption of Krakatau in 1883. This has been described by several writers[2]. About nine-tenths of the material consists of glass fragments with the characteristic features noticed above. The remainder is of comminuted crystals of plagioclase, magnetite, enstatite, and augite, the whole having the composition of an acid pyroxene-andesite.

We pass on to notice a few consolidated deposits (tuffs) of various composition.

An interesting study of ancient *acid tuffs* has been made by Mügge in the Devonian of the Lenne district in Westphalia. The rocks are associated with old soda-rhyolites ('Keratophyre' of the author), and have a similar composition. They are for the most part of compact type, and, though considerably altered, still retain much that was characteristic in their original structure. In particular, they often shew very clearly the peculiar form of the constituent ash-particles, bounded by concave curves, which clearly suggest broken up pumice[3]. Crystal-tuffs are also found.

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[1] *Cf.*, *e.g.*, Teall's figure of one of the Llanberis tuffs, pl. xlv, fig. 1.

[2] Murray and Renard, *Nature* (1884) xxix, 585–589; Cole, *Proc. Geol. Ass.* (1884) viii, 332–335; Joly, *Proc. Roy. Dubl. Soc.* (1884) *N. S.* iv, 291–299, pl. xii, xiii; Judd, *Rep. Krak. Comm. Roy. Soc.* (1888) 38–41, pl. iv.

[3] *Neu. Jahrb. für Min.*, Beil. Bd. viii, pl. xxiv, figs. 20, 21, *etc.* (1893). All the figures illustrating this paper are instructive. See also chromolithograph in Berwerth, Lief. iii.

Some of the Ordovician rhyolite-tuffs of Caernarvonshire have much resemblance to those just mentioned[1]. Others, there and in the Lake District, have evidently consisted of much more finely divided material, and have often lost all trace of their original characteristics by secondary changes. Embedded crystals usually occur (Glyder Fawr, *etc.*), but do not make up any large part of the mass. There are, however, beds made up very largely of small rock-fragments and broken crystals lying in a fine-textured matrix or united by a brown ferruginous paste. The rock-fragments are of various quartz-porphyries and granophyres, and sometimes detached spherules; the crystals are of acid felspar and decomposed augite (near Llanbedrog, *etc.*)[2]. Prof. Bonney[3] has described an agglomeratic type from the older rocks of the Llanberis district as consisting of fragments and lapilli of rhyolite and fragments of quartz and felspar embedded in an altered felspathic dust. Here some of the rock-fragments are of large size. Concerning the tuffs of the Arenig district there is little information, but examples have been described by Mr Cope[4] from Aran Mowddwy.

Rhyolite-tuffs occur at several places in Pembrokeshire. One from Llanrian shews a very characteristic micro-structure (fig. 64, *A*). Others have been described from Fishguard[5] and from St David's[6]. Good rhyolite-tuffs are found in the Malvern district (Knighton).

Some of the fine-textured rocks which have been styled 'porcellanite' and 'hälleflinta' are acid tuffs compacted by secondary silica and other substances. Examples occur in the St David's district (Clegyr Bridge, *etc.*) and in Charnwood Forest (Nanpanton). Rocks of the same general aspect in the Lake District (Bow Fell, *etc.*) are fine tuffs of intermediate composition.

A number of rhyolitic tuffs and breccias are described by

[1] Mügge, *l.c.*, pl. xxvii, fig. 41.
[2] *Bala Volc. Ser. Caern.*, 27.
[3] *Q. J. G. S.* (1879) xxxv, 312.
[4] *Pr. Liverp. G. S.* (1897) viii, pl. iv, v.
[5] Reed, *Q. J. G. S.* (1895) li, 175.
[6] Geikie, *ibid.* (1883) xxxix, 297–301.

Zirkel[1] from the Tertiary volcanic region of Nevada, while others occur among the ancient volcanic rocks of the eastern States[2].
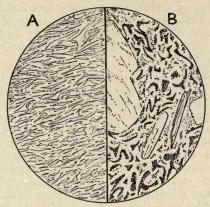
FIG. 64. ANCIENT PUMICEOUS TUFFS; ×20.

A. Rhyolitic Tuff (Ordovician), Llanrian, Pembrokeshire. Originally composed wholly of glass-fragments, the outlines of which are still partly discernible, despite their alteration [475].

B. Andesitic Tuff (Old Red Sandstone), Inverinan, Argyllshire. The outlines of many of the fragments are clearly indicated, owing to their being charged with magnetite-dust. There are also partly rounded crystals of plagioclase and an occasional flake of biotite [2385].

Trachyte-tuffs of various types are known in many of the newer volcanic districts of Europe and America, but they have not often been minutely studied. The rock known as 'trass' is, at least in part, of this nature. In the Siebengebirge is a considerable development of trachyte-conglomerate. The leucitophyres of the Eifel district are accompanied by tuffs of corresponding nature.

A good example of a hornblendic *andesite-tuff* is extensively developed at Rhobell Fawr[3] in Merioneth, an old volcano

[1] *Micro. Petrogr. Fortieth Parallel* (1876), 264–271.
[2] See, *e.g.*, G. O. Smith, *Geology of Fox Island, Me.* (1896) 39 and pl. I, fig. 4.
[3] Cole, *G. M.* 1893, 343.

probably of late Cambrian age. It is in great measure a crystal-tuff, the most conspicuous elements being perfect and broken crystals of brown hornblende and pale yellowish augite. Similar rocks, of Ordovician age, are found at Bail Hill in Ayrshire[1]. Tuffs with the general composition of hornblende- and especially of mica-andesites, enclosing broken crystals and lapilli, occur in the Old Red Sandstone of the Oban district[2] (fig. 64, B).

The majority of the Ordovician tuffs in the Lake District correspond in general composition with andesites and with basic andesites or basalts, but many of them have in addition angular fragments of rhyolite. Crystals of felspar are often seen, but do not make up a large part of the rocks, which are essentially of the compact type in most cases (fig. 63). Rolled pieces of lava of small dimensions may occur. In some localities the rocks consist mainly of a mixture of small lapilli with fragments of slate, grit, etc., often metamorphosed. Mr Hutchings has described an example from Falcon Crag near Keswick[3]. The finer tuffs of the district are often cleaved and highly altered (see below).

The cleaved tuffs of Cader Idris[4] in Merioneth also contain plenty of slate-fragments with felspar crystals and particles of scoriaceous andesite-glass converted into green palagonite, all set in a fine ashy matrix.

Other Ordovician tuffs consist largely of little fragments of formerly glassy and sometimes pumiceous andesite, now converted into a palagonite-like material of yellow or brown colour (e.g. Snead in Shropshire)[5]. Tuffs mainly of andesitic material are found also in the Bala series of Lambay Island, near Dublin[6].

Some interesting fragmental rocks of *basic* composition occur in the old volcanic series of St David's of early Cambrian

[1] Teall, *Ann. Rep. Geol. Sur.* for 1896, 39.
[2] Kynaston, *ibid.*, 54, and *Tr. Edin. G. S.* (1901) viii, 87–90, pl. III.
[3] *G. M.* 1891, 462.
[4] Cole and Jennings, *Q. J. G. S.* (1889) xlv, 423–431.
[5] Cole, *Q. J. G. S.* (1888) xliv, pl. XI, fig. 5.
[6] Gardiner and Reynolds, *Q. J. G. S.* (1898) liv, 140, 141; Sollas, *Pr. Geol. Ass.* (1893) 101, with figs. 7, 8.

or pre-Cambrian age. They are agglomeratic tuffs consisting chiefly of little fragments of basic lava, sometimes rounded but usually angular or subangular. In some there is very little matrix: it consists of fine *débris* of the same material as the larger fragments. Sir A. Geikie[1] has described specimens from Pen-y-foel and Pen-maen-melyn.

Among the basaltic rocks crystal-tuffs seem to be almost unrepresented. A common type consists of lapilli of basalt (glassy or altered) cemented by calcite, aragonite, limonite, *etc.* Widely distributed is the *palagonite* type[2] of Waltershausen, described from Sicily, Iceland, the islands of the Pacific, *etc.* This consists chiefly of little fragments of altered glassy basalt, usually of brown colour, often vesicular, and sometimes enclosing a few crystals of augite, olivine, or basic plagioclase; while the cementing material is obtained from the decomposition of the fragments, or may include calcite derived from calcareous matter contemporaneously deposited or by infiltration from without. Such rocks are widely represented among the older formations in this country. Palagonite-tuffs, as well as other basalt-tuffs, occur in Nevada, *etc.*[3]

Submarine tuffs of intermediate and basic composition occur, for example, abundantly in the Carboniferous in the basin of the Firth of Forth. Most of them contain some admixture of detrital or calcareous matter, but characteristic examples of tuffs, and in particular of palagonite-tuffs, are found. As described by Sir A. Geikie[4], the bedded deposits consist of a fine-textured matrix enclosing fragments of lava. The latter are the *débris* of already consolidated rocks rather than typical lapilli: they are largely vesicular, not only at the margin but throughout, and the vesicles are often cut by the external surface of the fragment. Calcite, delessite, *etc.*, occupy the cavities. A common feature is fragments of a transparent green or yellowish material re-

[1] *Q. J. G. S.* (1883) xxxix, 295–300, pl. ix, figs. 1, 2.
[2] For figures of palagonite-tuffs see Zirkel, *Micro. Petr. Fortieth Parallel*, pl. xii, figs. 3, 4; Rosenbusch, *Mass. Gest.*, pl. vi, fig. 4.
[3] Zirkel, *Micro. Petr. Fortieth Parallel* (1876), 272–275.
[4] *Trans. Roy. Soc. Edin.* (1879) xxix, 513–516, pl. xii, fig. 10. For examples of similar rocks of pre-Cambrian age, see R. D. Irving, *Copper-bearing Rocks of L. Superior* (1884), pl. xv.

sembling serpentine, which is evidently an altered vesicular glass, and is referred to palagonite. The matrix of these rocks has probably consisted of finely divided material of the same general nature as the larger fragments, but its structure is completely obscured by secondary changes, and the mass is stained green or brown. Tuffs of essentially similar characters are found in the Carboniferous of the Isle of Man (Scarlet Point)[1] and the Limerick district[2].

The tuffs associated with the Carboniferous of Derbyshire are in great part composed of true lapilli, often bordered, and having numerous vesicles not broken by the outline of the lapillus[3]. The material is a brown glass with globulites and crystallites and with crystals of olivine or plagioclase. These minerals are often replaced by calcite, and the same substance fills the vesicles and forms the cement of the rock.

Many basic tuffs have a calcareous cement. In some cases the calcite may have been derived from the destruction of lime-bearing silicates or introduced in solution from an extraneous source. There are, however, many submarine tuffs of all ages in which calcareous organisms have been accumulated contemporaneously with the volcanic material, giving rise to every gradation from a pure tuff to a pure limestone. Such deposits are forming at the present day in the neighbourhood of volcanic islands, and consolidated *calcareous tuffs*, often abounding in foraminifera, *etc.*, are beautifully represented among the Recent strata of the Solomon Islands[4], the Tonga group[5] (fig. 65), Torres Straits[6], *etc.*

Fine-grained tuffs, and in a less degree agglomerates, may receive, as already mentioned, a secondary *cleavage-structure* precisely similar to that observed in argillaceous rocks; and the cleavage is often accompanied by mineralogical changes.

[1] Hobson, *Q. J. G. S.* (1891) xlvii, 442, 443.
[2] Watts, *Guide*, 95.
[3] Arnold-Bemrose, *Q. J. G. S.* (1894) l, 625–642, pl. xxiv, figs. 4, 5, xxv.
[4] Guppy, *Trans. Roy. Soc. Edin.* (1885) pl. cxlv, *etc.*
[5] *G. M.* 1891, 251–256.
[6] Sollas and Cole, *Sci. Proc. Roy. Dubl. Soc.* (1891) vii, 124–126; Haddon, Sollas, and Cole, *Trans. Roy. Ir. Acad.* (1894) xxx, 436, 437, pl. xxv, fig. 6.

The cleaved tuffs or ash-slates of the Lake District have been noticed by Dr Sorby, and some of them described in detail by Mr Hutchings[1]. These rocks are of intermediate, and sometimes perhaps basic, composition, and the finely divided portions have undergone great secondary changes. Chlorite and dust or granules of calcite are often conspicuous, and
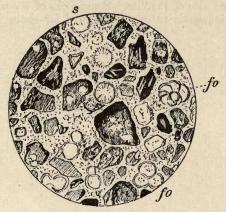
FIG. 65. CALCAREOUS TUFF, EUA, TONGA ISLANDS; ×20.

The fragments are mainly of brown-stained andesitic and basic lava, more or less glassy and altered to palagonite. These, with tests of foraminifera (*fo*), are enclosed in a calcareous matrix. Each foraminiferal chamber is occupied by calcite with radial fibrous structure, giving a perfect black cross between crossed nicols, and the same is seen in the little spherical bodies (*s*), which are doubtless detached chambers of *Globigerina* [1273].

when these have been removed by acid from the powdered rock, or from very thin slices, other minerals may be detected, especially minute sericitic mica, which gives bright polarization-tints. The needles of rutile, so characteristic of clay-slates, are not found, but there are sometimes granules of sphene (*e.g.* Kentmere). In some of these slates minute garnets play an important part (*e.g.* Mosedale, near Shap). In general

[1] *G. M.* 1892, 154–161, 218–228; see also *Pr. Liverp. G. S.* (1901) ix, 106–112, pl. VI, VII.

there has been an abundant separation of silica, partly as quartz, partly perhaps as chalcedony.

This is the general character of the finest slates of the Lake District, which are evidently greatly altered from their original state.   The coarser bands have a matrix of similar character enclosing lapilli and recognizable fragments of andesite and also of rhyolite.   Some rocks of a comparatively coarse agglomeratic nature are worked for slates in Borrowdale.

APPENDIX TO SEDIMENTARY ROCKS.

A few bedded rocks, not included in the foregoing chapters, deserve brief notice. They are deposits due, some to chemical, others to organic agency. We shall exclude the carbonaceous rocks (coal, *etc.*), which belong to the domain rather of fossil botany than of petrology.

There are certain salts which occur in beds, forming stratified rocks, and locally attain a great development. One of these is *rock-salt*, found in the Trias of Cheshire and Worcestershire and at various geological horizons in other countries. Besides admixture of other salts, the deposits contain more or less of clayey, organic, or other impurities. Rock-salt itself (sodium chloride) is colourless in slices, and has a strongly marked cubic cleavage and a low refractive index. It frequently contains microscopic brine-cavities of cubical shape.

Another mineral which may form a rock by itself is *gypsum*[1]. It occurs in allotriomorphic grains which may be very small. The strong clinopinacoidal cleavage is well marked; the refractive index is quite low, and the double refraction is weak (about equal to that of quartz). Gypsum is often associated with rock-salt.

The simple sulphate of lime *anhydrite* is also found as a rock (Val Canaria in Switzerland, *etc.*), building allotriomorphic to partly idiomorphic crystals or fibrous aggregates. The two strong pinacoidal cleavages are well marked; the refractive

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[1] Hammerschmidt notes that the heating of the Canada balsam in mounting may cause partial dehydration of the mineral, giving rise to little matted aggregates of anhydrite. On gypsum in general see Goodchild, *Proc. Geol. Ass.* (1888) x, 425–445.

index is low, but the double refraction very strong (equal to that of muscovite). The rock often encloses grains of rock-salt or of dolomite and other minerals. It is specially liable to conversion into gypsum, which may be seen in various stages, veins and patches of the latter mineral traversing the anhydrite mass. This involves an increase of bulk and phenomena of disruption.

Another mineral which sometimes forms a simple rock is *chalybite* or siderite, the ferrous carbonate. We have already seen that some iron-stones of this composition have been formed by metasomatic processes from limestones, but in other cases, such as the ironstone bands in the Coal-measures of Yorkshire, *etc.*, there is no evidence of such an origin. The mineral may be mixed with other carbonates in smaller proportions and with a variable quantity of argillaceous matter (clay-ironstone). Chalybite has the rhombohedral cleavage of the calcite-group of carbonates, and in its brownish-yellow colour resembles some impure dolomites.

Some siliceous rocks. Here we may notice certain siliceous rocks which do not, at least in the main, result from pseudomorphism of limestones. Some well-known examples of *cherts* fall under this head, the silica being derived from siliceous sponges, recognizable remains of which still form an important part of the rock. In the chert-beds of the Upper Greensand[1] in the Isle of Wight the sponge-spicules sometimes remain in their original condition, consisting of colloid (isotropic) silica, but more usually spicules and matrix are alike converted to chalcedony. The sponge-beds of similar age in the Weald district consist largely of colloid silica, but the spicules are represented by empty casts. The cherts of the Carboniferous limestones of Ireland[2] are found, in the best-preserved specimens, to consist largely of sponge-spicules, the matrix being also siliceous and doubtless derived from the dissolution of other spicules. Here the silica is always in the condition of chalcedony or quartz. The Yoredale cherts of Yorkshire and

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[1] Hinde, *Phil. Trans. Roy. Soc.* (1885), pp. 447, 448, pl. 40; for abstract see *Q. J. G. S.* (1889) xlv, 406, 407.
[2] Hinde, *G. M.* 1887, 441–443.

North-Wales are of similar character, with better preserved sponge-remains, and the same seems to be true of the Carboniferous cherts (Fr. phthanites) of Belgium, and of some other countries, including some of the 'Kieselschiefer' of the Germans.

Of great interest are the deep-sea deposits which give rise to siliceous rocks. The 'Challenger' Expedition[1] has shewn that these occur over extensive tracts of the ocean-floor in its deepest portions. Characteristic types are the *diatom-ooze*, essentially an accumulation of the frustules of diatoms[2], and the *radiolarian ooze*, made up mainly of the tests of radiolaria. There may be some admixture of finely divided volcanic material or decomposition-products or of foraminiferal remains. The equivalents of this radiolarian ooze are found in Recent and Tertiary *radiolarian earths* such as those of Barbados[3] and Trinidad[4], and, in a compacted form, in the *radiolarian cherts* of some of the older formations. The Ordovician cherts of the south of Scotland, described by Dr Hinde[5], shew in slices a faint cloudy appearance, giving a mottled effect between crossed nicols, but are frequently veined and stained with dark brown. In the transparent parts the radiolaria shew as shadowy circles defined by their interior being somewhat lighter than the surrounding matrix. In the stained parts the tests are replaced

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[1] See especially Murray and Renard, *Chall. Rep.*, *Deep-Sea Deposits* (1891) with plates (pl. xv, *etc.*).

[2] Diatomaceous deposits of more limited extent are found occupying the sites of old lakes at numerous places in the north and west of Scotland; Macadam, *M. M.* (1884) vi, 87–89, *etc.*: also at Toome Bridge on Loch Neagh; Pollok, *Sci. Pr. Roy. Dubl. Soc.* (1899) ix, 33–36, with figures. Similar deposits occur near Monterey, Cal. and White Plains, Nev.; Diller, 136, 137: also in the Tertiary of Richmond, Va. These pulverulent deposits of diatoms are styled 'Kieselguhr,' 'tripolite,' and 'diatomite.'

[3] See Jukes-Browne and Harrison, *Q. J. G. S.* (1892) xlviii, 174, 175; Nicholson and Lydekker, p. 34, fig. 12.

[4] Gregory, *Q. J. G. S.* (1892) xlviii, 538, 539. On a radiolarian earth from S. Australia see Hinde, *Q. J. G. S.* (1893) xlix, 221, pl. v.

[5] *Ann. Mag. Nat. Hist.* (1890) ser. 6, vi, 41–47, pl. iii, iv. On a somewhat similar rock from Mullion Island, Cornwall, see Hinde, *Q. J. G. S.* (1893) xlix, 215, pl. iv; on radiolarian cherts in the Culm of Devon, Cornwall, and Somerset, see Hinde and Fox, *Q. J. G. S.* (1895) li, 629–634.

by a dark substance, and may retain much of their original structure. The most considerable development of radiolarian cherts known is in the Devonian of Tamworth, N. S. W[1]. Here a deep-sea origin is inadmissible.

Radiolarian cherts and jaspers of Mesozoic age are known from several localities in the San Francisco district[2]. The presence of radiolaria or other siliceous organisms in cherts is not conclusive evidence that the bulk of the silica is of organic origin, and Lawson regards the Californian cherts as mainly deposited from submarine springs[3]. They shew every gradation from an isotropic mass of amorphous silica to a holocrystalline aggregate of quartz-granules, the crystallization beginning from distinct centres, as in the devitrification of a glass. The radiolaria are preserved in chalcedonic silica.

A peculiar type of siliceous deposit is the *sinter* of the hot springs and geysers of the Yellowstone Park, Iceland, and New Zealand. Mr Weed[4] has shewn that this material, consisting of colloid silica, is in great part secreted by filamentous algæ (Leptothrix, *etc.*). The resulting sinter or 'geyserite' does not always shew clear organic structures. Sinter is formed also in the same places by the evaporation of the water in which the silica was carried in alkaline solution.

[1] Edgworth David and Pittman, *Q. J. G. S.* (1899) lv, 33, 34; Hinde, *ibid.* 38–42, pl. viii, ix.
[2] Ransome (and Hinde), *Bull. Dep. Geol. Univ. Cal.* (1894) i, 198–200, 235–237; Lawson, *Amer. Geol.* (1895) xv, 348, 349, and 15*th Ann. Rep. U. S. Geol. Sur.* (1895) 422–426.
[3] *Cf.*, however, Fairbanks, *Journ. of Geol.* (1897) v, 65–68.
[4] *A. J. S.* (1889) xxxvii, 351; more fully in 9*th Ann. Rep. U. S. Geol. Sur.* (1890) pp. 613–676.

E. METAMORPHISM.

Using the term 'metamorphism' in a broad sense, we understand by it the production of new minerals, or new structures, or both, in pre-existing rock-masses. We must limit such a conception by supposing on the one hand that the changes produced are sufficient to give a distinctive new character to the rock as a whole, and on the other hand that they do not involve the loss of individuality of a rock-mass (*e.g.* bodily fusion must be excluded).

It is customary to distinguish *thermal* metamorphism, due to heat, and *dynamic* metamorphism, due to pressure. These can to some extent be considered separately, and we shall examine some of their results in the following pages. But, before doing so, we must notice that very important changes, which cannot reasonably be excluded from the domain of metamorphism, are set up in rock-masses without the intervention of either high temperature or great mechanical force. Many of these changes depend upon the access of circulating waters in communication with the atmosphere, and we may, if we please, roughly group them as meteoric or *atmospheric* metamorphism. In most cases, however, these processes involve some change in the total composition of the rocks affected, either a loss of some constituents or an addition of others (water, oxygen, carbonic acid, and other substances): in other words there is often *metasomatism* as well as metamorphism.

The common weathering-products of igneous rocks are results of such processes, but it is convenient, as already

remarked, to restrict the term metamorphism to cases in which the general mass of a rock is considerably altered : the serpentine-rocks are an example. It is important to observe, however, that the minerals produced by secondary actions of the kind here contemplated include some which are also common as original constituents of igneous rocks : we have already mentioned the occurrence in this way of secondary quartz, felspars, hornblende, *etc.* There is a frequent tendency of the new-formed substance to form as a crystalline extension of pre-existing crystals or grains of the same mineral (like the quartz in many quartzites); or again for a pre-existing mineral to be extended by an outgrowth of some allied mineral with the same crystalline orientation : *e.g.* one kind of plagioclase felspar may receive an extension of another kind, augite of hornblende, allanite of epidote.

The most striking examples of what we have termed atmospheric metamorphism and metasomatism are found among the sedimentary rocks. We have already remarked the conversion of sandstones to quartzites, the recrystallization of limestones[1] and their replacement by dolomite, iron-compounds, silica, *etc.*, and we have seen that very many argillaceous sediments have undergone extensive or almost complete reconstitution since they became strata.

More important is the evidence of the formation of crystalline schists on an extensive scale by metasomatic changes alone described by Prof. Van Hise in the Lake Superior region. In the upper part of the Penokee Iron-bearing Series[2] of Michigan and Wisconsin felspathic grits, greywackes, *etc.*, are traced into finely crystalline mica-schists, with biotite and muscovite, all relics of the clastic structure being finally obliterated. In the lower members of the same series[3] rocks consisting of

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[1] Stefani attributes to the influence of circulating waters the formation from Triassic limestones of the famous Carrara marble in the Apuan Alps : see *G. M.* 1890, 372, 373 (*Abstr.*).

[2] Van Hise, *A. J. S.* (1886) xxxi, 453–459 ; Irving and Van Hise, *Penokee Iron-bearing Series* in 10*th Ann. Rep. U. S. Geol. Sur.* (1890) 423–435, pl. xxxviii–xlii.

[3] Van Hise, *A. J. S.* (1889) xxxvii, 32–47 ; Irving and Van Hise, *l.c.* *Cf.* Hudleston, *Pr. Geol. Ass.* (1889) xi, 133–138.

impure carbonates mixed with chert have been converted into ferruginous quartz-schists, magnetite- and hæmatite-schists, magnetite- and hæmatite-bearing actinolite-schists, *etc.*, also by metasomatic processes (silicification and other replacements), apparently without the conditions of either thermal or dynamic metamorphism. Similar rocks occur in the Mesabe range, Minnesota[1].

We may now pass on to such changes affecting rock-masses as are more usually understood by the term metamorphism as employed in text-books. The changes are in part *mineralogical* (in most cases without any very important metasomatism), in part *structural*. These two lines of change are so connected that they cannot be considered quite separately: roughly we may say that mineralogical modifications are the more prominent in thermal metamorphism, and structural in dynamic.

While treating in turn the chief features of thermal and of dynamic metamorphism, we must remember that their effects may be associated or superposed in the same area, and the assigning of particular mineralogical changes to one or the other cause is in many cases still a question for discussion.

[1] Bayley, *A. J. S.* (1893) xlvi, 176.

CHAPTER XX.

THERMAL METAMORPHISM.

UNDER this head we include all changes produced in pre-existing rock-masses by the influence of high temperature[1]. In the simplest case this is brought about by the intrusion of an igneous magma in the neighbourhood ('contact' or 'local' metamorphism of many authors); but we must also include the effects of heat mechanically generated (thermal being then associated with dynamic phenomena), and those due to the internal heat of the Earth in a rise of the isogeotherms. These latter especially may affect rock-masses on a regional scale. We shall here avoid complication by drawing our examples, so far as is possible, from cases of thermal metamorphism produced by igneous intrusions.

Characteristic minerals. It will be convenient to refer briefly to the commoner minerals formed in thermal metamorphism, some of them being unknown or rare in igneous rocks. *Quartz* and felspars are widely distributed in metamorphic rocks of various kinds. The felspars include *orthoclase, albite, anorthite*, and various intermediate members of the plagioclase series. They are often perfectly clear, and when they occur as minute shapeless granules in a mosaic they may easily be mistaken for quartz without special optical tests[2]. The

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[1] For a discussion of various questions concerning thermal metamorphism see *Science Progress* (1894), ii, 185–201, 290–303.

[2] Becke has given a staining method, using aniline blue after etching with hydrofluoric acid. Plagioclase is deeply coloured, orthoclase only slightly affected, and quartz unchanged (for examples see Berwerth, Lief. III).

larger grains shew cleavage and sometimes characteristic twinning or some approach to crystal outline.

Both *muscovite* and *biotite* are found in metamorphosed rocks, the latter being very widely distributed. It is apparently a haughtonite and always strongly pleochroic, with a deep reddish-brown colour or, for vibrations parallel to the cleavage-traces, a very deep brown with a noticeable greenish tone. Intensely pleochroic haloes surround certain inclusions. Less usual than brown mica as a conspicuous mineral is a green *ripidolite* or a yellowish or greenish *chlorite*. In the fine-textured 'base' of argillaceous rocks, however, Mr Hutchings[1] notes that the conversion of impure micaceous material into an aggregate of muscovite and chlorite, so characteristic in the passage of clays and shales into slates, is also met with in thermal metamorphism, especially where there is no abundant production of biotite. Exceptionally we find the manganese-bearing chloritoid mineral *ottrelite*[2] (fig. 69, *A*). It builds flakes without special orientation, and freely encloses impurities: the lamellar twinning parallel to the base and a modification of hour-glass structure are noticeable[3].

Highly characteristic of the metamorphism of argillaceous and some other rocks are silicates rich in alumina. *Andalusite* forms more or less idiomorphic crystals with the prism-form and usually some traces of the prismatic cleavage. It is recognized by its moderately high refractive index with low double refraction (about the same as in labradorite) and straight extinction. When it shews any colour, it is pleochroic, giving a rose tint for longitudinal and a very faint green for transverse vibrations. It may be quite clear, or may contain numerous inclusions, certain enclosed minerals being surrounded by a pleochroic halo (bright yellow to colourless). In *chiastolite*[4] the elongated crystals contain a large amount of foreign matter, apparently carbonaceous, arranged in the fashion peculiar to the mineral (fig. 68). *Sillimanite* (*fibrolite*)

[1] *G. M.* 1896, 344, 345; 1898, 74, 75.
[2] See Hutchings, *G. M.* 1889, 214; Whittle, *A. J. S.* (1892) xliv, 270–277.
[3] Cohen (3), pl. xxii, fig. 4; xxx, fig. 3.
[4] *Ibid.* pl. xvii, fig. 4.

builds elongated prisms or needles, which in shape, cross-fracture[1], and refractive index resemble apatite, but have a much stronger birefringence (fig. 66). They are often crowded together in matted aggregates imbedded in quartz ('Faser-kiesel' or 'quartz sillimanitisé'[2]). *Cyanite*[3] or disthene is found less commonly, building more or less rounded crystals or grains, with pinacoidal cleavage and a cross-fracture corresponding with a gliding-plane. In thin sections it is colourless or pale blue, with pleochroism, and, owing to its high refractive index, shews a strong relief. Longitudinal sections give extinction-angles up to 31°. *Staurolite* forms good crystals, the larger ones always crowded with various inclusions[4]. When fresh, it is yellowish or reddish-brown with distinct pleochroism[5] and strong refringence and birefringence. This mineral, however, and in varying degree all the aluminous silicates, are very liable to decomposition, the characteristic product being white mica in minute scales (the 'shimmer-aggregate' of Barrow[6]). *Cordierite* is sometimes less easily recognized. It is commonly in shapeless grains crowded with inclusions, but sometimes builds pseudo-hexagonal prisms, basal sections of which occasionally shew the curious triple twinning[7]. The mineral rarely shews its colour and pleochroism in thin slices, but is sometimes stained of a yellow tint. The refractive index and double refraction are low.

The metamorphism of calcareous rocks gives rise to numerous silicates rich in lime, or in lime and magnesia. The pure lime-silicate *wollastonite* is colourless in thin slices, and shews lower refringence and birefringence than the augites. It is further distinguished by having its two principal cleavages and its direction of elongation perpendicular to its plane of symmetry, and consequently giving straight extinction. As a

[1] Cohen (3), pl. xlvii, fig. 2.
[2] *Ibid.* pl. xxxvii, fig. 3; Williams, *A. J. S.* (1888) xxxvi, pl. vi, figs. 2, 4; Barrow, *Q. J. G. S.* (1893) xlix, 338, pl. xvi, figs. 1, 2.
[3] Cohen (3), pl. xlii, fig. 4; Barrow, *l.c.*, 338, 339, pl. xvi, figs. 3, 4.
[4] Williams, *A. J. S.* (1888) xxxvi, pl. vi, fig. 3. On arrangement of inclusions see Penfield and Pratt, *ibid.* (1894) xlvii, 81–89.
[5] Cohen (3), pl. xxvii, fig. 1.
[6] *Q. J. G. S.* (1893) xlix, 340, pl. xvi, fig. 5.
[7] Cohen (3), pl. xxix, fig. 3.

rule, it occurs in quite small imperfect crystals.   The augites of metamorphosed limestones, *etc.*, are either non-aluminous (*diopside*) or aluminous (*omphacite*).   They build imperfect crystals or crystalline patches, take part in a finely granular mosaic, or occur as little globules enclosed in other minerals. The crystals are occasionally twinned on the usual law.   The green colour is often imperceptible in thin slices.   Both diopside and omphacite give extinction-angles of 38° or 40°, and it is not always possible to discriminate them, though the former is sometimes betrayed by its partial conversion into serpentine. The most common amphibole in these rocks is a colourless *tremolite* in imperfect crystals, crystalline patches, veins, or sheaf-like groupings.   It may shew a fibrous structure or a good hornblende-cleavage, and a rough cross-fracture is also common.   Green *hornblende* and blade-like *actinolite* are found in some rocks.   The lime-garnet *grossularite* forms well-bounded crystals, often of considerable size, with included pyroxene granules (fig. 72).   It is often feebly birefringent, and further shews between crossed nicols a polysynthetic twinning of a remarkable kind[1].   With this structure goes a strongly marked zonary banding, the concentric zones differing in birefringence. *Idocrase* occurs either in well-built crystals or in shapeless plates enclosing other minerals.   The cleavage and colour are usually not to be observed in thin sections.   The birefringence is variable, and a crystal often shews bands or lamellæ differing in interference-colours.   *Zoïsite* occurs in little prisms often grouped in sheaf-like fashion.   It is characterized by longitudinal cleavage-traces, high refractive index, low polarization-tints, and straight extinction.   *Epidote*, often associated with the last-named mineral, is usually in shapeless grains or granular aggregates, though it may present crystal-boundaries towards calcite, *etc.*   The cleavages are well-marked, the two sets of traces intersecting at about 65° in a cross-section. Twinning is uncommon.   The larger crystals shew the yellow colour and pleochroism.   Other distinctive characters are the high refractive index, very brilliant polarization-tints, and straight extinction in longitudinal sections.

[1] Cohen (3), pl. LII; also, for numerous figures, Klein, *Neu. Jahrb.* 1883, i, pl. VII–IX.

A characteristic mineral in metamorphosed dolomite-rocks is the pure magnesian olivine *forsterite*. It forms either crystals of tabular habit (fig. 73) or rounded grains, and by alteration gives rise to serpentine. In certain cases magnesia has crystallized in the form of *periclase*, in octahedra, or in rounded grains (*e.g.* in blocks ejected from Monte Somma, Vesuvius); but this passes readily by hydration into *brucite*, a clear, colourless mineral with one (basal) cleavage, straight extinction with the cleavage-traces, low refringence, and strong birefringence (nearly equal to that of augite).

Among other products of thermal metamorphism in various rocks may be mentioned common garnet, chloritoid, dipyre, magnetite and ilmenite, pyrite and pyrrhotite, sphene, rutile and anatase, spinels, corundum, and graphite. Further, the formation of a certain amount of isotropic matter is characteristic in some cases[1].

As a special mineral formed in metamorphosed rocks near an igneous intrusion may be noticed *tourmaline*. This mineral occurs in little grains, often in veins which represent cracks, or sometimes very abundantly as a constituent of a kind of contact-breccia. It is restricted to the neighbourhood of acid intrusions, and depends on an actual introduction of certain materials from the igneous magma. White mica has sometimes a similar occurrence.

Metamorphism of arenaceous rocks. The effects of thermal metamorphism in arenaceous rocks are simple or complex according to the homogeneous or heterogeneous nature of the deposits affected. In a pure quartz-sandstone or quartzose grit there are no degrees of metamorphism possible. If the temperature be sufficiently high, the whole will be recrystallized into a clear quartz-mosaic without a trace of the original clastic character. Short of this change, the sandstone will be unaltered, except in such minor points as the expulsion of the water from the fluid-pores of the quartz, an effect noticed by Sorby at Salisbury Crags. The homogeneous quartzite resulting from the complete metamorphism of a pure quartzose rock

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[1] On this and some other points see Hutchings, *G. M.* 1894, 36–45, 64–75.

is not difficult to distinguish from a quartzite formed by the deposition of interstitial quartz. There is no distinction of original grains and cementing material, no secondary growth upon original nuclei, but each element of the mosaic is clear and homogeneous, presenting an irregular boundary which fits into the inequalities of the adjoining elements. Such quartz-ites are locally produced in the Skiddaw grits abutting on the large granophyre mass at Ennerdale, in the Carboniferous sandstones near the Whin Sill of Teesdale, and in many other places.

If the original sediment contained felspar grains, not much altered, as well as quartz, the felspar is recrystallized with the quartz, and without careful examination is liable to be over-looked in the resulting mosaic.

Where a quartzose sandstone or grit has contained scattered decomposition-products, such as kaolin, calcite, and chloritic minerals, in small quantity, metamorphism produces a quartzite with granules of some accessory mineral. Thus, near the Shap granite, the grits in the Coniston Flags group have been transformed into a quartzite with granules of colourless pyro-xene, formed from kaolin and calcite. Similarly the chloritic minerals give rise to brown mica. A curious green mica occurs in the quartzite of Clova in Forfarshire.

The metamorphism of a specially pure type of siliceous rock has been described by Mr Horne[1] in the case of the Arenig radiolarian cherts of the south of Scotland, as they approach the Loch Doon granite. The final result is a mosaic of granular quartz with numerous minute round inclusions of biotite.

If the original rock was more impure, containing plenty of aluminous and other substances, the product of metamorphism ceases to have any apparent resemblance to a quartzite. Silicates of alumina, garnet, micas, etc., may be extensively produced, and the metamorphosed rock assume the aspect of a fine or even a coarse gneiss (fig. 66). Remarkable examples are presented by the Silurian grits and flags round the Old

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[1] *Rep. Brit. Ass.* for 1892, 712. *Cf. Ann. Rep. Geol. Sur.* for 1896, 46, and Teall, *Mem. Geol. Sur., Silur. Rocks Scot.* (1899) 640–642.

Red Sandstone granites of Galloway[1]. Here the chief con-
stituents are quartz, muscovite, a deep brown biotite, and
red garnet (colourless in slices), felspar being only subordinate.
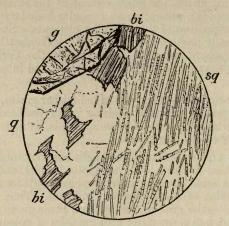
FIG. 66.   GARNET-SILLIMANITE-SCHIST OR GNEISS, A HIGHLY
    METAMORPHOSED GRIT, CLOVA, FORFARSHIRE;   × 20.

The right half of the figure shews an area of clear quartz full of little
prisms of sillimanite with characteristic cross-fracture (*sq*): to the left
are clear quartz (*q*), biotite (*bi*), and part of a large garnet (*g*) [1808].

The garnets, except at the margin of each crystal, are crowded
with minute granular inclusions: they tend to occur in clusters
moulded by clear quartz, a frequent association in many meta-
morphic rocks.   Nearer to the granite the texture of the rock
becomes coarser, and the muscovite and quartz are seen to be
crowded with narrow needles of sillimanite up to ·01 inch long.
The same minerals as before are present, with a few crystals
of plagioclase and rarely a little brown tourmaline.   At a
hundred yards from the granite margin the texture is very
coarse, the abundant white mica building plates half an inch
in length and relatively thick.   Dense matted aggregates of

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[1] Miss Gardiner, *Q. J. G. S.* (1890) xlvi, 569–580; Teall, *Mem. Geol.
Sur.*, *Silur. Rocks Scot.* (1899) 644–647.

sillimanite needles occupy the interior of the quartz and muscovite, leaving the borders of the crystals clear.   Some of the most altered rocks shew bands or streaks rich in particular minerals, such as lenticular patches of garnet set in clear quartz or streaks composed essentially of muscovite and sillimanite, dark mica being less plentiful (fig. 67).
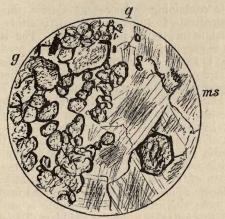
Fig. 67.   Garnet-sillimanite-schist or gneiss, a highly metamorphosed grit, Knocknairling Hill, New Galloway;   × 20.

The figure shews portions of two lenticular streaks, one consisting essentially of muscovite crowded with minute needles of sillimanite (*ms*), the other of garnet (*g*) set in clear quartz (*q*) [1173].

Some highly metamorphosed sediments in the eastern Highlands of Scotland are rich in cordierite, usually crowded with inclusions of other minerals and having round certain inclusions the characteristic pleochroic yellow haloes.   An example from the Buck of Cabrach in Banffshire consists of cordierite and white mica in allotriomorphic crystals and a mosaic of microcline, with some quartz, andalusite, magnetite, and biotite.   This rock has a massive structure, but others in the same district are gneissose and schistose[1].   Corundum,

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[1] Teall, *Mem. Geol. Sur. Scot., Expl. Sheet* 75 (1896), 36, 37, 45; and *Ann. Rep. Geol. Sur.* for 1896, 18, 19.

as well as sillimanite, spinel, *etc.*, occurs in some of these cordierite-bearing rocks[1].

Metamorphism of argillaceous rocks. The effects of thermal metamorphism in clays, shales, or slates depend in the early stages of alteration on the mineralogical, and in the later stages on the chemical, composition of the rocks affected.

In strata containing carbonaceous matter, this is one of the first ingredients to suffer change. It is either dissipated and expelled or converted into graphite. The latter is in some cases aggregated into little dark spots, producing one type of what is known as 'spotted slate' (Ger. Knotenschiefer). This peculiarity may be seen in otherwise unaltered strata, and it disappears with advancing metamorphism. The minute needles of rutile so abundant in slates also seem to be rather readily affected, giving place to stouter crystals of the same mineral, or less commonly to anatase or brookite. Another early effect of metamorphism is the production of little flakes of brown mica (probably the haughtonite variety of biotite) from chloritic substances, *etc.* With this there may be a crystallization of iron-ores (magnetite or pyrites). In some cases a chloritic mineral or ottrelite is formed instead of the mica. In rocks rich in alumina chiastolite is produced concurrently with biotite[2], *e.g.* in the Skiddaw district (Bannerdale, Roughton Gill, *etc.*, fig. 68).

With advancing metamorphism graphitic spots and chiastolite-crystals are lost, and the metamorphism begins to affect the whole body of the rock, the chief products formed being usually quartz and biotite. Of these the latter often has its flakes oriented in accordance with the original lamination or cleavage of the rock, and we have thus one type of mica-schist (Ger. Glimmerschiefer). These rocks may have no trace of the original clastic nature of the deposit, except perhaps some minute angular quartz-grains. They sometimes shew a spotted character quite different from that mentioned above, and consisting in little ovoid spaces free, or relatively free, from the

[1] Teall, *Summary of Progress Geol. Sur.* for 1898, 86–88; *Pr. Geol. Ass.* (1899) xvi, 63, 64 (Monadh Driseag near Loch Awe).

[2] For good coloured figures see Teall, pl. xxxiii, fig. 2 (Skiddaw); Fouqué and Lévy, pl. iii, fig. 1 (Brittany).

flakes of biotite which crowd the rest of the rock. Such spaces often shew distinctly crystalline properties, giving extinction parallel with their length, and in many cases, at least, they are ill-developed crystals of andalusite. They
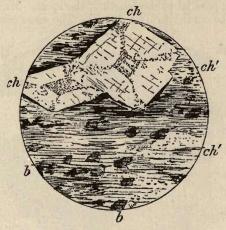
FIG. 68. CHIASTOLITE-SLATE, SKIDDAW SLATE METAMORPHOSED
BY GRANITE, BANNERDALE, SKIDDAW; ×20.

Besides the good cross-sections of chiastolite (*ch*), shewing character-istic arrangement of enclosed impurities, there are imperfectly developed crystals (*ch'*) clearly detected by using polarized light. In the general mass of the rock the chief metamorphic effect is the production of little flakes of biotite (*b*) [1111].

may be observed in the Skiddaws of the Caldew and Glendera-terra valleys. When andalusite is better developed, it appears in clear crystal-grains or in crystal-plates enclosing other minerals : both forms are seen in the Skiddaw district, where andalusite-mica-schists have been extensively formed[1]. Other minerals, such as white mica and little garnets, occur more locally (Sinen Gill, Grainsgill, *etc.*).

[1] On the various stages of metamorphism in the Skiddaw district, see especially Rosenbusch (translated) in *Naturalist*, 1892, 119, 120.

As another example of well-marked spots due to the development of imperfect crystals, we may take the Coniston Flags near their contact with the Shap granite[1]. Here the spots are small and ovoid, with numerous inclusions, but give a distinctly crystalline reaction, the essential mineral extinguishing parallel to the length of the spots. Mr Hutchings finds it to be cordierite[2] (fig. 69, B). The same mineral forms
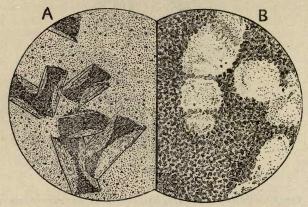
FIG. 69; × 20.

A. Ottrelite-slate (metamorphosed Cambrian slate), Ottré, Ardenne, Belgium. Crystals of ottrelite crowded with inclusions [1565].

B. Cordierite-Mica-schist (metamorphosed Coniston Flags), near Shap granite, Wasdale Beck, Westmorland. The ovoid spaces free from biotite indicate imperfect crystals of cordierite [866].

somewhat larger spots in some of the metamorphosed Skiddaw Slates of the Caldew valley, and here some of the imperfect crystals shew the characteristic composite twinning (Swineside)[3].

Various types of spotted and flecked rocks due to metamorphism have been styled spilosite, Fleckschiefer, Fruchtschiefer, Garbenschiefer, etc., and shew spots and patches of

[1] Q. J. G. S. (1891) xlvii, 320, pl. xii, fig. 5.
[2] Hutchings, G. M. 1894, 65.
[3] G. M. 1894, 169.

very various dimensions. In some they are evidently ill-formed crystals (*e.g.*, cordierite); in others the true nature of the spots is not very clearly understood. Mr Teall[1] compares with the typical 'spilosite' of the Harz some slates near Tremadoc

Fig. 70. Andalusite-mica-schist, metamorphosed Skiddaw Slate, close to granite, Sinen Gill, Skiddaw; ×20.

The rock consists of andalusite, biotite, and quartz, with subordinate muscovite and magnetite. It has not a very marked schistose character, and would be styled Hornfels by the German writers. All the lower half of the figure is occupied by a large crystal-plate of andalusite, enclosing numerous flakes of mica and needles of sillimanite [1446].

altered by large sheets of diabase. Here the spots are almost invisible in a slice viewed in ordinary light, but become conspicuously dark between crossed nicols. This seems to be due to numerous minute overlapping scales of chlorite. A micaceous mineral occurs more sparingly, and an aggregate of granules having the refraction and double refraction of quartz and felspar. Similar phenomena are seen in other parts of North Wales, *e.g.*, near the granite of Ffestiniog, and in many other countries[2]. Other metamorphosed slates near

[1] *Brit. Petr.* 218.
[2] Clements describes a rock of this type in metamorphosed Huronian slates near Mansfield, Mich.; *A. J. S.* (1899) vii, 86.

Tremadoc have a banded rather than a spotted character, thus answering to the 'desmoisite' rather than the 'spilosite' of the Harz geologists.

In extreme cases of metamorphism the rocks lose all spotted, and frequently all banded and schistose, structures, passing sometimes into an extremely compact, fine-textured mass of quartz, micas, iron-ores, *etc.* (Ger. Hornfels, Fr.
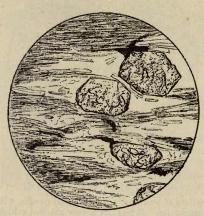
Fig. 71. Graphitic mica-schist, Blair Atholl, Perthshire ; cut perpendicularly to the schistosity ;   × 20.

The rock consists mainly of quartz and sericitic mica, with some finely divided graphite. There are also numerous dodecahedra of garnet, each in the centre of a lenticular streak or 'eye' of quartz [1834].

cornéenne, 'hornstone' of some writers). Andalusite, garnet, *etc.*, characterize different types (Ger. Andalusithornfels, Granathornfels, *etc.*). Some highly metamorphosed strata, however, have a marked schistose character, usually due to micas of sericitic habit following old structural planes in the rock. Dark mica usually predominates, but white is also frequent. Red garnet is common in mica-schists of this kind, and other minerals may occur, according to the original chemical composition of the rock. A well-marked zone of graphitic mica-schists is known in the Central Highlands, and

shews the characters of a thermally metamorphosed rock (fig. 71). The graphite doubtless represents carbonaceous matter of organic origin.

The Ordovician slates near the Leinster granites are converted into mica-schists with staurolite and graphite. Locally they shew spots, which develop into crystals of andalusite, sometimes of considerable size. Patches of rock enclosed by the granite exhibit a higher grade of metamorphism, with development of staurolite, garnet, idocrase, zinnwaldite mica, tourmaline, actinolite, *etc.*[1]

In slates which originally contained a considerable amount of muscovite or of finely divided felspathic matter, or at least had not become much impoverished in alkalies, the phenomena of metamorphism are somewhat different from those sketched above. Chiastolite is not formed, and andalusite does not usually figure largely in the more metamorphosed rocks, while new-formed white mica occurs abundantly with the biotite or to its exclusion. A good example of the type characterized by white mica is afforded by the slates of Charnwood Forest near a granitic intrusion at Brazil Wood[2]. Here the ragged flakes of muscovite enclose subordinate biotite with parallel intergrowth: a chlorite is also present, besides clear quartz and granules of opaque iron-ore. Near the Whin Sill of Teesdale Mr Hutchings[3] finds the Lower Carboniferous shales converted in some beds to a minute aggregate wholly of muscovite and chlorite. In many cases of contact-metamorphism material introduced into the metamorphosed rocks from an invading magma has given origin to special minerals not dependent on the nature of the strata affected. The commonest of these special minerals is tourmaline. It has been formed abundantly in many of the slates bordering the granitic intrusions of Cornwall[4] and Devon. Besides the brown or blue tourmaline, the metamorphosed rocks consist of quartz, micas,

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[1] Watts, *Guide*, 39, 40.
[2] Bonney, *Q. J. G. S.* (1877) xxxiii, 783. These slates are probably composed in great part of volcanic material.
[3] *G. M.* 1896, 348–350 ; 1898, 74–77, 125–128.
[4] Allport, *Q. J. G. S.* (1876) xxxii, 408–417. For a striking instance see Hawes on the Albany Granite, N. H., *A. J. S.* (1881) xxi, 21–32.

chlorite, andalusite, *etc.*   Some of the less altered slates have
a spotted character in which the spots are imperfect crystal-
grains of andalusite.   The more altered rocks are mica-schists.

In the neighbourhood of some basic intrusions there seems
to have been more important metasomatic change, brought
about especially by a transference of soda from the magma to
the rocks undergoing metamorphism.   Some of the 'adinoles'
of the Harz are ascribed to this action.   They consist essen-
tially of a fine-textured mosaic of quartz and albite with
sometimes other minerals.   Mr Teall[1] compares with adinole
a rock at Y Gesell near Tremadoc, which has the same mineral
composition, with the addition of minute scales of mica and
chlorite.   In an adinole near a diabase intrusion in the
Huronian slates of Mansfield, Michigan, more than half the
rock consists of albite, the other chief constituents being
actinolite and quartz[2].   As an example apparently of a like
transformation in arenaceous and even siliceous rocks, we may
note a case on Angel Island, San Francisco, where, according
to Ransome[3], not only felspathic sandstones but even radio-
larian cherts are converted to glaucophane-schists, composed of
quartz, albite, glaucophane, biotite, *etc.*

Apart from any introduction of soda, *etc.*, a very im-
portant feature in the metamorphism of many argillaceous
rocks is the abundant new formation of felspars.   This is
probably a quite common occurrence in the advanced stages
of metamorphism, but very careful study is needed to dis-
tinguish the felspar from quartz when it occurs in a minutely
granular mosaic.   Good instances are furnished by the Con-
iston Flags near the Shap granite.   In shales near the Whin
Sill of Teesdale, Mr Hutchings[4] finds spherical aggregates of
quartz and felspar fibres.

An example of extreme metamorphism is afforded by the
Silurian shales near the New Galloway granite[5].   The rocks

[1] *Brit. Petr.* 219–221.

[2] Clements, *A. J. S.* (1899) vii, 87, 88.

[3] *Bull. Geol. Dep. Univ. Cal.* (1894) i, 212–219, 223–226; pl. XIII,
figs. 3, 4.

[4] *G. M.* 1895, 124.

[5] Miss Gardiner, *Q. J. G. S.* (1890) xlvi, 570–573.

consist of quartz, light and dark micas, the former predominating, red garnet, and subordinate felspar. The mica gives a foliated character to the mass, and the quartz tends to aggregate in little knots or lenticles.

Metamorphism of calcareous rocks. It appears that, under the conditions which rule in ordinary cases of metamorphism by heat, carbonic acid is not driven off from lime-carbonate, except in presence of available silica to replace it. Thus a pure limestone is not altered in chemical composition by metamorphism. It is, however, at a sufficiently high temperature, recrystallized into a fine or coarse-grained marble, in which all traces of clastic and organic structures are effaced. This is seen locally in the Mountain Limestone against the Whin Sill of Teesdale, in the purer parts of the Coniston Limestone near the Shap granite, etc.

Most metamorphosed limestones, however, have had sufficient impurities to give rise to various lime-bearing silicates, which are found in the recrystallized limestone as crystals, crystalline aggregates, patches, plumose tufts, etc. The chief characteristic minerals have been noted above. Two or more of them often occur in association, and sometimes with a regular arrangement. Thus some beds of the Coniston Limestone near the Shap granite enclose large crystals of idocrase in stellate groups or nests, each nest surrounded by a shell composed largely of felspar. Metamorphosed limestones in Glen Derry, near the Cairngorm granite, contain aggregates of garnet. In the Glen Tilt rocks we find chiefly amphibole-minerals—tremolite, actinolite, and green or even brown hornblende. A band of crystalline limestone near Tarfside in the highly metamorphosed area of Forfarshire has green hornblende, zoisite, felspar, quartz, sphene, and other minerals. Fine examples of the production of lime-silicates (wollastonite, scapolite, felspars, pyroxenes, etc.) are furnished by the crystalline limestones bordering the gabbros of the Adirondacks and the Lake Champlain district[1]. Crystalline limestones with accessory minerals of metamorphic origin may attain a considerable development in areas of 'regional'

[1] Kemp, *Bull. Geol. Soc. Amer.* (1894) v, 223; (1895) vi, 241–262; C. H. Smyth, jr., *ibid.* 263–284.

metamorphism. The 'cipollino' of the Italian geologists is a rock of this kind containing mica and other silicates.

The most striking effects, however, are produced in very impure limestones or in calcareous shales, slates, or tuffs. In these the carbonic acid is completely eliminated, and the whole converted into a *lime-silicate-rock* (the German 'Kalk-silikathornfels' or 'Kalkhornfels'). It appears too that quite a moderate amount of calcareous material in shales, tuffs, *etc.*, suffices to make the metamorphism take this line instead of those described under the head of argillaceous rocks. The metamorphosed rocks consist of aggregates, usually but not always fine-grained and compact, of silicates rich in lime with sometimes quartz, pyrites, or other minerals. Several of these minerals occur in association, giving rise to rocks of complex constitution ; and beds differing slightly in the amount and nature of their non-calcareous material result in different mineral-aggregates. Numerous types are illustrated by the metamorphosed Coniston Limestones at Wasdale Head, where they abut on the Shap granite. The purer beds, as already remarked, are converted into crystalline limestones, but the calcareous shales and tuffs have had their carbonate-minerals completely destroyed. The Upper Coniston Limestone is extensively converted into a compact porcellanous-looking rock, in which irregular crystalline patches and grains of pyroxenes and other lime-bearing silicates are recognizable. In some specimens wollastonite predominates, in others augite (ompha-cite), in others tremolite; and various associations of these and other minerals can be noted in thin slices[1]. Anorthite and probably other felspars are present, sometimes in irregular crystal-plates or patches with ophitic habit, sometimes in minute granules. In the compact rocks are sometimes enclosed stellate groups of large crystals (idocrase or augite), each group surrounded by a shell chiefly of plagioclase crystals[2]. A bed in the Lower Coniston Limestone is converted into a mass of garnet and idocrase. The garnet (grossularite) is in good crystals enclosing pyroxene-granules and enclosed by the

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[1] *Q. J. G. S.* (1891) xlvii, pl. xii, figs. 3, 4.
[2] *Ibid.* (1893) xlix, pl. xvii, fig. 6.

clear idocrase[1] (fig. 72). It shews the optical anomalies noted above[2]. A considerable variety of lime-silicate-rocks is found in the Cromdale Hills, *etc.*, in the eastern Highlands of Scotland[3].
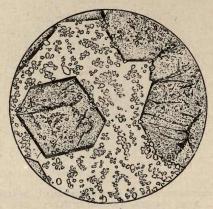
FIG. 72. GARNET-IDOCRASE-ROCK (METAMORPHOSED CONISTON LIME-STONE), NEAR SHAP GRANITE, WASDALE HEAD, WESTMORLAND; ×20.

The highly refringent crystals are the lime-garnet (grossularite) and the clear mineral forming the matrix is idocrase. Both enclose abundant pyroxene-granules [2730].

More remarkable effects are produced when there has been an introduction of boric acid into the rock during the metamorphism. At South Brent, on the border of the Dartmoor granite, Busz has remarked a Devonian limestone converted into an aggregate of birefringent garnet and interstitial datolite. Axinite is another mineral occurring in like connexion.

Of special interest is the *dedolomitization* of dolomite-rocks by metamorphism. Here the dolomite is reduced to calcite, while its magnesia enters into new minerals. One

[1] *Q. J. G. S.* (1891) xlvii, pl. XII, fig. 1.
[2] *Ibid.* p. 312.
[3] Teall, *Mem. Geol. Sur. Scot., Expl. Sheet* 75 (1896), 36, 44.

well-marked type arising in this way consists of calcite and forsterite (fig. 73), and such a rock may be converted into a
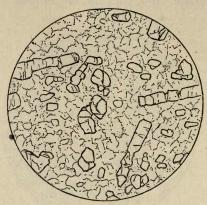
FIG. 73.   FORSTERITE-MARBLE (METAMORPHOSED CAMBRIAN DOLOMITE),
NEAR GRANITE, KILCHRIST, SKYE;   × 20.

Shewing crystals of olivine (forsterite) in a calcite-mosaic [2398].

serpentinous marble or 'ophicalcite.'   Even a pure dolomite-rock, free from siliceous or other impurity, may be dedolomitized; and in this way have been formed the rocks known in the Tirol as 'predazzite' and 'pencatite,' which are granular aggregates of calcite and brucite, the latter probably arising from the hydration of periclase.   These and other types are found among the metamorphosed equivalents of the Cambrian dolomite-rocks at Ledbeg in Sutherland, on the border of the Loch Borolan intrusion[1], and also in Skye, where the same group of strata is highly metamorphosed by the Tertiary granite and gabbro.

Metamorphism of igneous rocks.   Although the thermal metamorphism of plutonic rocks, lavas, volcanic ashes, *etc.*, has not yet received very much attention, it offers many points of interest and importance.   Many of these features

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[1] Teall, *Summary of Progress Geol. Sur.* for 1900, 153, 154.

are exhibited by the Ordovician volcanic series of the Lake District in the neighbourhood of the granite intrusions of Shap and Eskdale.

The acid igneous rocks are much less susceptible to thermal metamorphism than those of intermediate and basic composition. The rhyolites near the Shap granite do not, as a rule, shew any changes that can be clearly attributed to the effects of heat. Where, however, decomposition-products existed in the original rocks, they have given rise to metamorphic minerals. In particular, the green pinitoid substance is converted into a mixture of white and brown micas. The coarsely spheroidal ('nodular') rhyolites illustrate this point. The spheroids had, prior to metamorphism, been altered in the usual fashion into complex nodules having concentric shells of rhyolite substance and of weathering-products. In the metamorphosed nodules the shells of unweathered rhyolite remain unaltered, the flinty siliceous zones are converted into quartz-mosaic with a little mica, and the pinitoid substance is changed into biotite and muscovite. In the cracks which divided the shells there may be a little blue tourmaline.

The fragmental rocks associated with these rhyolites were of much less acid composition, and were probably more weathered prior to the metamorphism. Hence they shew more change, the production of biotite being often observed. As in argillaceous rocks, little spots relatively clear of mica are sometimes present : these shew a crystalline reaction and may be andalusite. The spots disappear with more complete metamorphism, but crystals or grains of andalusite or cyanite are sparingly developed, and finally the rock is completely recrystallized into a finely granular mosaic with a certain amount of biotite, a little opaque iron-ore, *etc.* Relatively large crystals of felspar enclosed in the tuffs are replaced by a new felspar-mosaic, only the general outline of the original crystal being preserved.

In the intermediate and basic rocks metamorphism may give rise to important changes. Diorites are metamorphosed in the Malvern range, the results, however, being complicated by dynamic changes. As described by Dr Callaway[1], the chief

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[1] *Q. J. G. S.* (1889) xlv, 485, *etc.*

effect clearly referable to heat is the replacement of horn-
blende by a deep brown biotite in the vicinity of an intruded
granite[1]. It appears that the hornblende had been, at least
to some extent, previously converted into a chloritic mineral.
The plagioclase is stated to give rise to white mica. The same
author[2] describes the metamorphism of diorite by a granitic
intrusion at Galway Bay, where recrystallized plagioclase is
observed, and the hornblende has given place to a chloritic
mineral, epidote, and rarely biotite.

The Carrock Fell granophyre, in Cumberland, has produced
metamorphism in a very basic type of gabbro. In some ex-
amples the apatite and iron-ores are unchanged, the turbid
felspars become clear, and the augite is converted into green
actinolitic hornblende or into biotite. The latter occurs chiefly
near the grains of iron-ores, from which it has probably taken
up some ferrous oxide and titanic acid[3]. In other specimens
the gabbro shews more complex changes.

The metamorphism of diabases by granitic intrusions has
been noticed by Allport[4] in Cornwall, by Lossen in the Harz,
etc. Specimens from these districts shew in various stages the
conversion of augite into hornblende and the recrystallization
of the felspar. The hornblende produced is mostly green, but
in the neighbourhood of the iron-ores (ilmenite) it is sometimes
brown. Brown mica or scaly patches of chlorite may be found
instead of hornblende, and these often give indications of being
formed not directly from augite but from its decomposition-
products. In the Isle of Skye similar effects are to be observed
in diabase dykes cut off and metamorphosed by the granite of
Beinn an Dubhaich (fig. 74).

The augite-andesites on the west side of the Shap granite
afford fine examples of thermal metamorphism. They had
undergone considerable change prior to the post-Silurian

[1] On production of a red mica in a diorite, see also McMahon,
Q. J. G. S. (1894) 1, 351.

[2] *L.c.* p. 495.

[3] *Q. J. G. S.* (1894) 1, pl. xvii, fig. 4. See also Sollas on Carlingford
district, *Trans. Roy. Ir. Acad.* xxx, 493–496, pl. xxvi, fig. 8, xxvii, figs.
10–16.

[4] *Q. J. G. S.* (1876) xxxii, 407–427. For figs. see Teall, pl. xvii, and
xxi, fig. 2.

intrusion of the granite. Chloritic minerals, calcite, chalcedony, and quartz had been formed from the pyroxene and
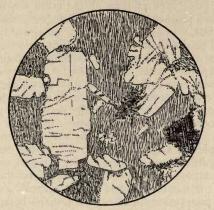
FIG. 74. METAMORPHOSED DIABASE DYKE, CLOSE TO GRANITE,
KILCHRIST, SKYE; × 20.

The augite is totally transformed to a pale, rather fibrous hornblende, except round the granules and skeletons of iron-ore, where its place is taken by biotite. The felspar crystals have become quite clear, but narrow chloritic veins traversing them have been converted to hornblende [3207].

felspar, and were partly disseminated through the rock, but especially collected in little veins and in the vesicles. These alteration-products were the elements most readily affected by heat. The chloritic mineral has been converted into biotite, or, where it was associated with calcite, into green hornblende (notably in the vesicles): chalcedonic silica has been transformed into crystalline quartz[1]. The rocks are more altered nearer the granite, and new minerals appear, such as a purplish-brown sphene, magnetite, and pyrites; the plagioclase phenocrysts are replaced by a mosaic of new felspar substance; and finally the whole mass of the rock is found to be reconstituted, the ground becoming a fine-textured mosaic of clear

[1] *Q. J. G. S.* (1891) xlvii, 294–298; pl. xi, figs. 4, 5.

granules. Mr Kynaston[1] has described similar effects in the
Old Red Sandstone andesites bordering the Cheviot granite.

A more basic type of lava, on the north side of the Shap
granite, shews phenomena on the whole very similar to the
preceding ; but, owing to the larger percentage of lime present,
the minerals produced are in part different. Green hornblende
predominates over biotite among the coloured constituents of
the metamorphosed rocks, and an augite, colourless in slices,
is also formed, especially in veins and amygdules. Epidote
is another characteristic mineral, and sphene, pyrites, and
magnetite occur as before. Especially noteworthy is the form-
ation of numerous lime-bearing silicates from the contents of
the vesicles : grossularite occurs, as well as hornblende and
actinolite, epidote, augite, and quartz. In the centre of the
largest amygdules some residual calcite is found, recrystallized
but not decomposed[2]. A basic hypersthene-bearing lava (the
Eycott type) is metamorphosed by the Carrock Fell gabbro[3],
the bastite pseudomorphs after hypersthene being converted
into a pale hornblende. Here the transformation of the rocks
is not always complete, the large labradorite phenocrysts being,
as a rule, not recrystallized into a mosaic, but only cleared of
their dusty inclusions (fig. 75). The metamorphosed Ordovi-
cian lavas near the Galloway granites[4] recall in many respects
the Shap rocks. A lime-garnet is frequently met with, and
new felspar occurs both in the body of the rock and in the
amygdules.

The Tertiary basaltic lavas of Skye are often considerably
metamorphosed by the later intrusions of gabbro and grano-
phyre. One interesting result is the formation of felspar in
the amygdules[5]. It is produced, together with epidote, zoisite,
actinolite, etc., mainly at the expense of soda-lime-zeolites.
In the mass of the rock the chief change is usually the
conversion of the augite to greenish fibrous hornblende. In
the highest grade of metamorphism, however, hornblende is

[1] Tr. Edin. G. S. (1901) viii, 18–26.
[2] Q. J. G. S. (1893) xlix, 360–364, pl. xvii, figs. 1–4.
[3] Ibid. (1894) l, 332.
[4] Teall, Ann. Rep. Geol. Sur. for 1896, 47 ; Mem. Geol. Sur., Silur.
Rocks Scot. (1899) 647–650.
[5] Q. J. G. S. (1896) lii, 386, 387.

not produced, augite being found both in the body of the rock (recrystallized in common with the felspar) and in the amygdules (associated with new felspar which replaces zeolites).
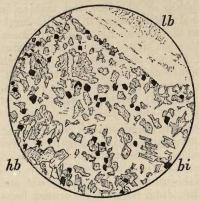
FIG. 75. METAMORPHOSED BASIC LAVA ENCLOSED IN THE GABBRO OF CARROCK FELL, CUMBERLAND; × 20.
The rock was originally a hypersthene-basalt belonging to the Eycott Hill group (see fig. 46). The porphyritic felspars have become clearer (*lb*), their large inclusions disappearing; the pyroxenes or their weathering-products have been converted chiefly into a pale hornblende (*hb*) or locally into biotite (*bi*); the magnetite has recrystallized in good octahedra; and the felspars of the ground-mass are now a clear aggregate, which appears almost homogeneous in natural light [1550].

The tuffs of basic and intermediate character near the Shap granite have much resemblance to the lavas as regards their metamorphism. Brown mica is the usual ferro-magnesian mineral formed, amphibole being less common. Magnetite is never abundant, and sphene is wanting. The most metamorphosed rocks are completely reconstituted into a very fine-textured aggregate of clear granules, in which lie flakes of biotite parallel to either original lamination or cleavage, producing a kind of mica-schist. Felspar crystals enclosed in the tuffs are either transformed into pseudomorphs of epidote or recrystallized into a mosaic[1].

[1] *Q. J. G. S.* (1893) xlix, pl. xvii, fig. 5.

Metamorphism in crystalline schists, etc.   On this subject there is not a large amount of information, and it appears that crystalline schists of various kinds are, as a whole, less susceptible to thermal changes than sedimentary rocks. The metamorphism of phyllites and mica-schists has been studied in the Adamello range, in the Riesengebirge, in New Hampshire[1], on the Hudson River[2], *etc.* In some respects the phenomena resemble those seen in argillaceous strata, the production of biotite, andalusite, *etc.*, being characteristic ; but there are sometimes quite special peculiarities, in particular the formation of minerals very rich in alumina.   Cordierite is sometimes extremely abundant, while pleonaste and other spinels and pure corundum are noted in several localities.

In the southern Highlands of Scotland Mr Clough has observed the crystalline schists to be metamorphosed by the granitic intrusions of the Garabal Hill district.   Within a mile of the junction the albite-schists begin to develop small prisms of andalusite, which increase in size and abundance, and at the same time nests of dark mica become plentiful.

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[1] Hawes, *A. J. S.* (1881) xxi, 21–32.
[2] G. H. Williams, *ibid.* (1888) xxxvi, 254–266.

CHAPTER XXI.

DYNAMIC METAMORPHISM.

IN this chapter will be noticed some of the effects, mineral-
ogical and structural, produced in rock-masses by the operation
of great mechanical forces. Among the mineralogical changes
we ought logically to separate those due to pressure from those
due to mechanically generated heat, the latter belonging rather
to the preceding chapter. This distinction we shall make, so
far as our actual knowledge goes.

The consideration of dynamic metamorphism in comparat-
ively yielding rock-masses has already been partly anticipated
in the chapter devoted to argillaceous sediments : phenomena
more striking, or at least more easily investigated, are now to
be noticed in crystalline and other rocks of more stubborn
consistency.

Strain-phenomena in crystalline rocks. A frequent
effect of strain in the component crystals of a stubborn rock-
mass is a modification of the optical properties, which at once
becomes apparent between crossed nicols. Instead of being
dark throughout for certain definite positions, a crystal shews
dark shadows which move across it as the stage is rotated, owing
to the directions of extinction varying from point to point.
These *strain-shadows*[1] are best seen in quartz, and are very
common in the granitic and gneissic rocks, quartzites, *etc.*, of
countries like the Scottish Highlands or the older parts of

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[1] Mr Blake styles this appearance 'spectral polarization.' It is
spoken of by some foreign writers as 'undulose extinction.' .

Norway, which have been the theatre of great crust-movements. Again, a mineral such as garnet, normally isotropic, may become birefringent (*e.g.*, in the Eddystone gneiss).

Flexible minerals, such as micas, often shew *bending* of their crystals, or, again, they yield by a shearing movement analogous to lamellar twinning parallel to definite directions known as *gliding-planes* (Ger. Gleitflächen). In some minerals, such as the plagioclase felspars, the gliding-planes coincide
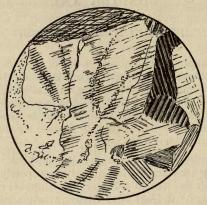
FIG. 76. SECONDARY TWIN-LAMELLATION IN PLAGIOCLASE FELSPAR, DUE TO STRAIN, IN GABBRO, ILGERSHEIM, NAHE DISTRICT; × 20, CROSSED NICOLS.

In places where the strain has been greatest the crystals have yielded along cracks. The mineral at the top of the figure is diallage converted into hornblende [1408].

with natural twin-planes[1], and the *secondary twinning* can be distinguished from original lamellation only by its inconstant character and its relation to bending or other strain-phenomena. It is very clearly seen in such rocks as the norites of Hitterö, Seiland, and Bekkafjord in Norway[2], where the original twin-lamellæ of the felspars are rather broad. Sometimes, in one crystal, the closeness of the secondary lamellæ is seen to increase

[1] Judd, *Q. J. G. S.* (1885) xli, 363–366, pl. x, fig. 1.
[2] Cohen (3), pl. LXXIX, figs. 1, 2.

with the strain, until the crystal has yielded along a crack or a granulated vein (fig. 76). In some rocks there seems to be evidence of the microcline-structure being set up in orthoclase as a result of strain.

Quartz sometimes shews *rows of fluid-pores* marking directions of shearing-strain, and parallel to actual planes of faulting if the crystal has yielded[1]. The lines of pores can be traced through contiguous crystal-grains; or entering another mineral, such as felspar, they may become actual planes of discontinuity.

It appears that the *schiller-structures*[2], so characteristic of certain minerals in deep-seated rocks, may also be produced as secondary phenomena by pressure. A typical structure is that in which cavities of definite form and orientation ('negative crystals') are developed along certain planes, and filled, or partially filled, by material dissolved out from the enclosing crystal. Hypersthene affords a good example. The 'solution-planes' (Ger. Lösungsflächen) proper to a mineral are parallel to one or more crystallographic planes; but after a secondary lamellar twinning has been set up in a crystal, the gliding-planes become the easiest solution-planes. Pyroxenes, felspars, and olivine are minerals often affected by schiller-structures.

Crystals of brittle minerals subjected to stress have often yielded by actual *cracks*, which may have a definite direction throughout the rock, being perpendicular to the maximum tension, and so parallel to the maximum pressure. This is sometimes seen in quartz and felspars, but most commonly in the garnet of granulites, eclogites, gneisses, and crystalline schists. As a further stage, the portions of a fractured crystal may be separated and rolled over, or drawn out in the direction of stretching or flowing movement in the solid rock. It is noticeable that quartz shews these phenomena much oftener than felspar: the former mineral, though harder than the latter, is more brittle.

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[1] Judd, *M. M.* (1886) vii, 82, pl. III, fig. 1.
[2] Judd, *Q. J. G. S.* (1885) xli, 374–389, pl. x–xii; *M. M.* (1886) vii, 81–92, pl. III.

Cataclastic structures. The phenomena of internal fracture and crushing of hard rocks ('cataclastic' structures of Kjerulf) are to be seen in endless variety in some regions of great mechanical disturbance. They may be developed in less or greater degree ; they may affect some or all of the mineral constituents of a composite rock ; they may or may not tend to a parallel arrangement of the elements. In one type the rock-mass breaks up along definite surfaces of sliding, the material bordering the cracks being often ground down by friction : this is *brecciation in situ.* The irregularly intersecting surfaces divide the rock into angular fragments ; but these may be rolled over and their angles rubbed off, so that a 'friction-conglomerate' as well as a 'friction-breccia' may arise, especially along faults and thrust-faults (*e.g.,* Lake District). According as the new structure is on a large or a small scale, the fragments may be recognizable pieces of rocks or portions of constituent crystals of an originally crystalline rock.

Again, we sometimes find the larger elements of a rock—grains of quartz, crystals of felspar, *etc.*—surrounded by a border of finely granular material furnished by the grinding down of the crystal itself and adjacent ones. This is the *morter-structure* (Ger. Mörtelstructur) of Törnebohm. As a further stage, the finely granular portion of the rock may make up the chief part of its bulk, forming a matrix which encloses portions of crystals not yet destroyed but indicating by irregular polarization their strained condition. Beautiful examples are seen among the crushed quartzites and gneisses of Sutherland (fig. 77).

In many cases mechanical forces having a definite direction have caused uncrushed fragments to assume an eye-shaped or *lenticular* form (Ger. Augenstructur) with their long axes perpendicular to the maximum pressure, and so parallel to one another and to any schistose structure in the matrix (fig. 80, *A*). In such cases the crushed matrix usually has a more or less well-marked parallel structure or *schistosity*, in part analogous to slaty cleavage. The final result of the grinding down and rolling out processes is the type of rock named *mylonite* by

Professor Lapworth[1], in which, except perhaps for occasional uncrushed 'eyes,' all original structures are lost. In these much crushed rocks the 'eyes' no doubt represent in many cases porphyritic crystals, usually of felspar, in what was once

FIG. 77. ADVANCED CATACLASTIC STRUCTURE IN GNEISS, SOUTH SLOPE OF BEINN MOR OF ASSYNT, SUTHERLAND; × 20.

The greater part of the rock is completely broken down, and has partly taken on the parallel structure of a mylonite. A large grain of quartz is only partly crushed, and this between crossed nicols shews strain-shadows [1641].

an ordinary igneous rock. It is evident, however, that, in the absence of such indications, it must often be impossible to determine by microscopical study alone the nature of a rock whose original structures have been totally obliterated.

Mineralogical transformations, etc. In extreme stages of crushing of crystalline rocks, the changes produced are by no means purely mechanical. In consequence of the stress and subsequent relief a *recrystallization* of minerals may be effected, resulting in the clear, finely granular aggregate which forms a large part of some dynamo-metamorphic rocks[2].

[1] See Page (Lapworth), *Introd. Text-book Geol.* 12th ed., figs. on p. 107.
[2] *Cf.* Teall, p. 175, figures.

It must be remembered, however, that thermal metamorphism due to mechanically generated heat may complicate the strictly dynamic changes.

Further, atomic as well as molecular rearrangement has operated in greater or less degree in any dynamo-metamorphic rock not of the simplest constitution. Certain *mineralogical transformations* seem to be characteristic of dynamical metamorphism, being either developed by the action of great pressure or at least facilitated by pressure even when they can also take place without that condition[1]. It should be noticed that in crystalline, and generally in hard, rocks, these mineralogical changes begin before any important structural modifications are produced.

One characteristic change is the production of colourless mica at the expense of alkali-felspars. The mineral may be formed at the margin of a crystal squeezed against its neighbours or on surfaces of lamination or of movement in a felspathic rock : in such cases it takes the filmy form known as sericite. Or it may replace the interior of a crystal partially or almost wholly. Potash-felspar gives rise to muscovite, soda-felspar to paragonite.

A characteristic alteration in the soda-lime-felspars results in the minutely granular aggregate which has been called 'saussurite,' and is not always of precisely the same nature[2]. The soda-bearing silicate of the felspar separates out as very minute clear crystals of albite, while the lime-bearing silicate, in conjunction with other constituents of the rock, goes to form minerals rich in lime. Zoisite is a characteristic mineral, or its place may be taken by yellow or colourless epidote ; and needles of actinolite may also occur. (Compare fig. 78.)

The conversion of plagioclase into scapolite under dynamic action seems to be a more complex process, involving the presence of sodium chloride in solution[3].

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[1] See G. H. Williams, *Bull.* 62 *U. S. Geol. Surv.* (1890) Ch. I.
[2] Teall, 149–152. For a somewhat similar process of ' granulation ' of plagioclase resulting in a fine mosaic of albite, *etc.*, see Hyland, *G. M.* 1890, 205–208. *Cf.* Williams, *l.c.* 58–60, 68, 69, figures.
[3] Judd, *M. M.* (1889) viii, 186–198, pl. IX.

Other changes common in dynamic metamorphism are the conversion of olivine into tremolite or anthophyllite and talc,
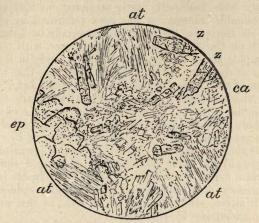
FIG. 78. SAUSSURITE-GABBRO, NORWEGIAN BOULDER ON THE YORKSHIRE COAST; ×20.

The portion figured consists of patches of pale greenish fibrous hornblende or actinolite (*at*), calcite (*ca*), and chlorite, prisms of zoisite (*z*), grains of epidote (*ep*), and little clear crystals of secondary felspar. The so-called 'saussurite' is a similar aggregate on a more minute scale [1049].

and the production of granular sphene at the expense of ilmenite or other titaniferous minerals. Augite gives rise when crushed to chlorite. The conversion of augite or other pyroxenes into green hornblende is also a common feature in regions of dynamic metamorphism : perhaps this is one of the transformations that should be ascribed to the heat generated in the crushing. It is a very wide-spread phenomenon[1].

The borders ('reaction-rims') sometimes noticed at the junction of two different minerals in a crystalline rock have in many cases been attributed to dynamic metamorphism. (See above, p. 77.)

[1] See, *e.g.*, R. D. Irving, *A. J. S.* (1883) xxvi, 27–32 ; G. H. Williams, *ibid.* (1884) xxviii, 259–268 ; Teall, *Q. J. G. S.* (1885) xli, 133–144.

Illustrative examples. After the above remarks it will be sufficient to mention a few cases in illustration of what is a very wide and only partly explored field of research. Much valuable information has been published by observers in various European districts, and especially by Lehmann in his work on the Saxon Granulite Mountains, with numerous photographic plates[1]. The most complete study in English of a region of dynamic metamorphism is perhaps that by G. H. Williams of the 'greenstone-schists,' *etc.*, of the Lake Superior region, which further contains a general summary of knowledge on the subject[2]. The dominant types of rocks in the areas there studied have been basic eruptives, probably true lavas in great part, and these are now represented by chlorite- and hornblende-schists. Gabbros, diorites, granites, and quartz-porphyries have also been included, and shew their appropriate types of alteration. The author traces in detail the processes of uralitization, chloritization, epidotization, saussuritization, sericitization, *etc.*, as well as the structural changes undergone by the rocks.

In our own country, and especially in some parts of the Scottish Highlands, the phenomena of dynamic metamorphism are exhibited on an extensive scale[3]. Dykes in the western part of Sutherland shew very clearly the conversion of diabase into hornblende-schist, and an instance of this has been described in detail by Mr Teall[4]. The augite is transformed into green hornblende, and the felspar has recrystallized in water-clear grains, while the titaniferous iron-ore has also been altered, giving rise frequently to granular sphene. These mineralogical changes may be produced without any schistose structure, but the massive hornblendic rock further becomes in places a typical hornblende-schist. This is at Scourie : other examples are seen near Unapool, on Loch

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[1] *Entstehung der Altkrystallinischen Schiefergesteine, etc.* Bonn (1884), Atlas.

[2] *The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan, Bull.* 62 *U. S. Geol. Surv.* (1890) Ch. I, VI, figures and plates.

[3] See Report in *Q. J. G. S.* (1888) xliv, 429–435.

[4] *Q. J. G. S.* (1885) xli, 133–144, pl. II ; *Brit. Petr.* pl. XIX, XX, pp. 197–200.

Glencoul, and near Loch Assynt (fig. 79).   At Lochinver
dykes of enstatite-peridotite pass into an anthophyllite-schist,
consisting of matted aggregates of anthophyllite prisms or
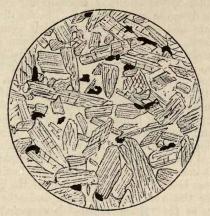
FIG. 79.   AMPHIBOLITE OR HORNBLENDE-SCHIST, FROM THE META-
MORPHISM OF A DIABASE DYKE, LOCH ASSYNT, SUTHERLAND;   × 20.

The rock now consists essentially of idiomorphic hornblende and
clear secondary felspar, with some magnetite.   The slice is cut parallel
to the schistosity, which therefore is not apparent in the figure [1664].

needles with little patches of brilliantly polarizing talc and
large rhombs of carbonates[1].

   Near Loch Assynt and in other places the Lewisian gneiss
is traversed by zones of crushing, within which the rock is
completely reconstituted, and from the granitoid assumes the
'granulitic' structure.   The rock so metamorphosed shews a
rather fine-textured mosaic of clear quartz and felspar, enclos-
ing imperfect crystals of green hornblende and ragged flakes
of brown mica instead of the original pyroxene.   There is a
marked parallel structure and some tendency in the several
minerals to collect into little lenticular aggregates.   The basic

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[1] Mr Teall speaks of one of these rocks as a talc-gedrite-siderite-schist.
In other examples the amphibole mineral is a monoclinic one (tremolite).

and ultrabasic dykes involved in these crush-zones are metamorphosed in the manner just described.

Some of the above-mentioned changes are perhaps to be ascribed rather to the effects of mechanically generated heat than to pure dynamic metamorphism. In the district farther east there are also some phenomena which seem to point to thermal effects, *e.g.* the production of brown mica in the Torridon Sandstone near the ' Beinn Mòr thrust-plane.' But, in proportion as the rocks affected give evidence by increasing schistosity of thorough mechanical degradation and sliding movement, those mineralogical transformations which seem to belong to pure dynamic metamorphism become more general. Near the great ' Moine thrust-plane ' the sericitization of the acid rocks and the chloritization of the basic ones reach their fullest development in connection with the maximum display of mechanical deformation. Detailed petrographical observations on this interesting district are not yet forthcoming, and the same must be said of the region east of the great thrust-faults, where the complex of gneissic and other crystalline rocks known as the ' Moine schists' is supposed by some to represent the old gneiss and other rocks of the west completely transformed by dynamic agencies.

Illustrations of dynamic metamorphism are furnished in the Central Highlands and in Ireland by various members of the Dalradian series of Sir A. Geikie. The so-called 'green schists' are ascribed by that geologist partly to the crushing of basic lavas and tuffs. Some of these rocks again have the appearance of intrusive diabases, in which every stage of crushing into chloritic schists, *etc.*, can be traced (North Esk, Kincardineshire).

Gradual transitions from massive diorite to hornblendeschists may be studied in Anglesey, especially between Holland Arms or Gaerwen and Menai Bridge[1]. In the processes by which these schistose rocks have been produced the felspar has often been destroyed, and is represented in great part by epidote, which is often abundant. The granular sphene, which is often seen, is probably derived in part from ilmenite, as well

[1] Blake, *Rep. Brit. Ass.* for 1888, 406.

as from the original sphene of the diorite. The hornblende has recrystallized in imperfect elongated crystals of green colour with marked parallel orientation. Locally the place of this mineral is taken by a beautiful pleochroic glaucophane, and a rock near the Anglesey Monument[1] is a glaucophane-epidote-schist, with little trace of any other mineral, except veinlets of clear secondary felspar. The pleochroism of the glaucophane (bright blue to pale lilac) and the epidote (yellowish green to pale yellow) makes a slice of this rock a very striking object.

The name 'amphibolite' has often been applied to rocks, usually more or less markedly schistose, in which hornblende is the dominant mineral. Many of them are doubtless the results of dynamic action on diorites and sometimes on diabases and gabbros. Two or three types from the Scottish Highlands have been figured by Mr Teall, including an epidote-amphibolite from Glen Lyon, Perthshire[2], and a zoisite-amphibolite from near Beinn Hutig, in Sutherland[3].

Interesting phenomena of dynamic metamorphism have been described by Smyth in the gabbros of the Adirondacks at Russell, St Lawrence County, N.Y.[4] The original rocks consisted essentially of labradorite and augite. From the former mineral has arisen scapolite and sometimes a saussurite-like aggregate; from the latter a scaly green hornblende. In a further stage of alteration cataclastic effects become marked, all the constituents becoming granulated, while the hornblende increases in amount. In the final stage the rock has taken on a gneissic structure, the cataclastic features are lost in total recrystallization, the scapolite has been reconverted to felspar, but of a more acid variety than the original labradorite, and part of the hornblende seems to have passed again into augite.

The 'porphyroids' of some authors are, for the most part, quartz-porphyries more or less modified by dynamic metamorphism. They have received a rough schistosity, which is accentuated by films of 'sericitic' mica, formed at the expense

[1] Blake, *G. M.* 1888, 125–127; Teall, pl. xlvii, figs. 1, 2.
[2] Teall, pl. xxviii, fig. 2.
[3] Teall, pl. xl, fig. 2. *Cf.* actinolite-schist with zoisite, pl. xxviii, fig. 1.
[4] *A. J. S.* (1896) i, 273–281.

of the felspar. The rock of Sharpley Tor in Charnwood Forest is a good example. Similar features are shewn by the Llanberis mass of quartz-porphyry at numerous points on its south-eastern edge, especially near Llanllyfni (fig. 80, B). Some of the 'porphyroïdes' of the Meuse Valley shew a similar schistose structure with much filmy mica. The same plentiful produc-tion of sericite in connection with a secondary schistosity is seen in the acid lavas; e.g. the old rhyolites, compact and spherulitic, of the Lenne, in Westphalia[1]. A different type is illustrated by the rhyolite-gneiss of Berlin in Wisconsin[2]. Here the chief transformations to be noted are the setting up of a microperthitic structure in the plagioclase phenocrysts and the recrystallization and orientation of the ground-mass.

The phenomena of dynamic metamorphism in argillaceous sediments (phyllites, etc.) have received some notice in a former chapter. The other groups of sedimentary rocks have been less studied from this point of view. Some of the phenomena observable in the arenaceous rocks and quartzites of Suther-land[3], culminating in complete mylonitization, we have already alluded to. Interesting mechanical effects are produced where alternating gritty and slaty beds have been subjected to crushing. Some remarkable cases have been described by Mr Lamplugh in the Skiddaw Slates of the Isle of Man; and Prof. Watts has shewn how the structures seen in the field are repeated on a small scale in slices of the rocks[4].

Calcareous rocks again are susceptible of considerable transformations, chiefly of the nature of structural rearrange-ment, when subjected to intense mechanical forces. Excellent examples are afforded by the Ilfracombe and other Devonian limestones, to which Dr Sorby[5] drew attention many years ago. These often shew, not only a highly developed slaty cleavage, but also a deformation of the individual fragments (such as crinoidal remains, etc.) of which they are largely composed, besides curious phenomena resulting from solution

[1] Cf. Science Progress (1894), ii, 55, 56.
[2] Weidman, Bull. Geol. and Nat. Hist. Sur. Wis. No. III (1898).
[3] Teall, pl. XLVI, fig. 2.
[4] Q. J. G. S. (1895) li, 563–597, pl. XX, XXI.
[5] Phil. Mag. (1856) xi, 26–34; Presid. Addr. 1879, Q. J. G. S., xxxv (Proc.), 57–59. See also Marr, G. M. 1888, 218–221.

having proceeded at the places of greatest pressure and simultaneous crystallization at the places of greatest relief. The cleaved limestones near Ilfracombe have a microscopic 'eyed' structure, owing to the preservation of uncrushed lenticles of the original rock (fig. 80, *A*). The salite-bearing limestone of
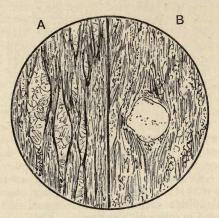
FIG. 80. SCHISTOSE STRUCTURES SET UP BY CRUSHING; × 20.

A. Devonian limestone, Ilfracombe: with uncrushed 'eyes' or lenticles [783].

B. Quartz-porphyry, Llanllyfni, Caernarvonshire: the schistose structure accentuated by films of secondary mica ('sericite') [87].

Tiree[1] in the Hebrides also illustrates well the crushing of a crystalline calcareous rock and the production of a fluxional schistose structure of varying perfection. This structure winds past the more resisting grains of salite, felspar, *etc.* (of detrital origin), and in the corners of the 'eyes' so left are uncrushed relics of the original calcite-mosaic.

[1] Bonney, *G. M.* 1889, 485.

CHAPTER XXII.

VARIOUS CRYSTALLINE ROCKS.

In this final chapter we shall consider briefly certain groups of crystalline rocks, some of very wide distribution, the classificatory position of which is in some doubt, owing to divergence of opinion concerning their origin. It will be evident on consideration that this difficulty arises in great measure from the grouping together under one descriptive name and definition of rocks whose common characteristics have originated in quite different ways. Until more complete knowledge may lead to a true genetic classification, we must be content to bear in mind that such names as 'crystalline schist,' 'gneiss,' and 'granulite' do not stand for natural groups, but are of merely descriptive significance; and we notice that various examples of them have already figured in the preceding pages.

Crystalline schists.   Under the general title of crystalline schists[1] (Ger. krystallinischen Schiefer) are comprised rocks of distinctly crystalline texture which possess a parallel arrangement of some or all of their elements, often with a tendency to the aggregation of particular constituents into streaks (foliation), and which have in consequence the property of splitting with more or less facility in a definite direction (schistosity).

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[1] Many English writers use the name 'schist' simply in this sense. This practice is liable to cause confusion, since 'schiste' is used in France (as formerly in this country) for an ordinary shale.

The structures due to the parallel orientation of crystals are various, and should be distinguished. Mr Blake[1] recognizes the 'quincuncial,' in which the crystals which give the structure (*e.g.* flakes of mica) are scattered promiscuously through the rock, but in parallel position ; the 'linear,' in which these crystals occur in lines, as well as having a general parallelism ; and the 'elemental,' in which the orientation is shewn, not by some particular constituent, but by all the elements of the rock. Further, some degree of aggregation of the several constituent minerals into streaks may give rise to an inconstant banding or to lenticular structures (Ger. 'flaser') on a small scale. The degree of schistosity imparted by these structures depends partly upon the minerals which figure in them, being most marked for flaky and acicular crystals (like mica and actinolite).

It must be observed, as already pointed out, that the meaning thus attached to the term 'crystalline schist' is a purely descriptive one, founded upon structural features which, as we have already seen, may arise in very diverse ways. The rocks included by such a name are not to be regarded as a natural group. A similar remark applies to the special names, mica-schist, hornblende-schist, *etc.*, used for different kinds of crystalline-schists. For another reason, too, such names are lacking in precision, indicating, as they do, only one of the component minerals of a complex rock. Further information may be embodied, if necessary, in epithets (*e.g.* garnetiferous mica-schist) or in compound names (*e.g.* andalusite-mica-schist). Again, such terms as diorite-schist and limestone-schist are sometimes used to indicate that the rock so named has the mineralogical composition of a diorite or a limestone with a schistose structure.

While much difference of opinion exists as to the interpretation of particular areas, it is now generally admitted that the crystalline schists as a whole are metamorphic rocks owing their present distinguishing characters in some cases to thermal, in other cases to dynamic agency[2]. We have studied in the

[1] *Rep. Brit. Ass.* for 1888, 379, figs. 5–7.
[2] For a summary of views on this question and for much valuable information the student should consult the series of papers on *Les Schistes Cristallins* contributed by a number of writers to the Inter-

two preceding chapters numerous types of crystalline schists (as well as non-schistose rocks) belonging to the two divisions thus indicated. The facts there detailed enable us in a considerable number of cases to tell with some confidence from what type of original rock a given crystalline schist has been produced, and to ascertain whether its metamorphism is the result of heat or of mechanical forces. In other cases one or both of these questions must be left in doubt.

We may remark that, while in rocks resulting from thermal metamorphism foliation and schistosity follow the direction of pre-existing structural planes (laminæ of deposition, cleavage, flow of lavas, *etc.*), in crystalline schists due to dynamic agency the new structures have their direction determined by the forces that produce them, and tend to obliterate, instead of emphasizing, any original structural planes in the mass affected.

Gneisses. The term 'gneiss' is now used to denote, not a rock of some defined composition, but any crystalline rock possessing a *gneissic structure*. By this is to be understood a banded or streaky character due to the association or alternation of different lithological types in one rock-mass or to the occurrence of bands or lenticles specially rich in some particular constituent of the rock. The structure is often found on a relatively coarse scale in rocks of granitoid texture, so that it is to be observed rather in the field or in large specimens than in microscopical preparations. It may, however, be associated with foliation on a smaller scale or with a partial parallel disposition of the elements of the rock. Gneisses, in this sense, may have the chemical and mineralogical composition of acid or intermediate or basic rocks, or may belong to types without parallel among the known products of igneous magmas.

It is generally recognized that gneisses as thus defined have originated in more than one way, but much difference of opinion exists as to the interpretation of the facts in particular districts. We shall note here the three cases which are probably of the most general importance.

national Congress of Geologists at London, 1888; pp. 65–102 of the *Compte Rendu* (1891). The French and German contributions are translated in *Nature*, Sept. 20, 27, Oct. 4 (1888).

(i) We have already seen that gneisses may originate by the thermal metamorphism of some sedimentary (and volcanic) rocks. The New Galloway rocks and the staurolite-, cyanite-, and sillimanite-bearing gneisses of the South-eastern Highlands are examples. The abundance of aluminous silicates is characteristic, and so also is quartz as an essential constituent in rocks with only a low percentage of silica. Under this head are probably to be included such rocks as the biotite-gneiss of the Black Forest and the rock known as 'kinzigite,' consisting essentially of garnet, biotite, and plagioclase, besides the hornblende-gneisses of the Odenwald, the Wahsatch, *etc.* All these have the chemical composition of sedimentary rocks; Rosenbusch styles them 'paragneisses,' in contra-distinction to 'orthogneisses,' which have the composition of, and are believed to represent, igneous rocks. In these latter there remain, as we shall see, two possible explanations of the gneissic structure.

(ii) It appears that gneissic banding may be set up, more particularly in plutonic rocks, by dynamic agency, *i.e.* by the mechanical deformation of a rock-mass originally heterogeneous or of a complex in which one rock was traversed or veined by a different one. In such a case we should expect to find further some degree of foliation and schistosity and usually lenticular structures, quasi-porphyritic 'eyes,' or other characteristic features. Numerous examples have been cited by Reusch from the western coast of Norway and by other observers elsewhere. Mr Teall[1] has applied the hypothesis of mechanical deformation to gabbros, granites, and diorites with gneissic and schistose structures in the Lizard district. Gen. McMahon[2], on the other hand, considers that these structures were impressed on the rocks while still only partially consolidated. He compares the Lizard rocks with the gneissic granites about Dalhousie, *etc.*, in the Himalaya region[3], which he believes to have been intruded in a partially consolidated state and to have assumed at that time their gneissic and foliated structures. Mr Middlemiss[4], however, ascribes these structures in the

[1] *G. M.* 1886, 481–489; 1887, 484–493.
[2] *G. M.* 1887, 74–77.
[3] *G. M.* 1887, 212–220; 1888, 61–65.
[4] *Mem. Geol. Sur. Ind.* (1896) xxvi, 65, *etc.*

Himalayan gneisses to dynamic metamorphism operating on the solid rocks.

(iii) There is no doubt that gneissic banding may be an original character in plutonic rocks, dating from the time when the rock in question was still fluid or partly fluid, and due to the different portions of a heterogeneous magma being drawn out in a flowing movement. A remarkable example is described by Sir A. Geikie and Mr Teall[1] in certain Tertiary gabbros in Skye. These rocks shew a striking alternation of light and dark bands due to differences in the relative proportions of the constituent minerals of the gabbro (labradorite, augite, olivine, and titaniferous magnetite). Some narrow bands are composed entirely of pyroxene and iron-ore. The authors compare these rocks with the ' Norian ' gabbros and anorthosites of North America and, as regards structures, with the Lewisian gneisses of the North-west Highlands.

These latter, apart from the innumerable dykes by which they are traversed, present much variation in character. In the north, between Cape Wrath and Loch Laxford, hornblendic and micaceous gneisses predominate. From Scourie to beyond Lochinver and Loch Assynt the prevalent type is a pyroxenic gneiss[2], consisting essentially of augite or hypersthene (Kylesku), felspars, and quartz. There are also acid types, consisting mainly of felspars and quartz ; while, on the other hand, the dominant rock encloses portions very rich in green hornblende. Hornblendic and micaceous gneisses predominate again about Gairloch and Loch Torridon, and a coarse hornblendic gneiss occurs in Lewis (Stornoway) besides other types. Many of these rocks shew in varying degree the effects of dynamic metamorphism, but the authors named consider that much of the banding (as distinguished from foliation) may be ascribed to original conditions attending the intrusion of igneous magmas.

In the South-eastern Highlands (Forfarshire and Kincardineshire) Mr Barrow[3] has described certain micaceous gneisses which are clearly igneous intrusions separable from the metamorphic gneisses, alluded to above, with which they are

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[1] *Q. J. G. S.* (1894) l, 645–659.
[2] Teall, pl. XL, fig. 1.
[3] *G. M.* 1892, 64, 65 ; *Q. J. G. S.* (1893) xlix, 330–335.

associated. In one phase the rocks consist essentially of quartz, peculiar rounded crystals of oligoclase, muscovite, and biotite. Another phase shews abundant microcline, with a corresponding diminution of oligoclase, while at the same time the white mica predominates increasingly over the brown, and builds larger crystals. The author makes it clear that the remarkable features of these igneous gneisses are due in the main to crust-movements at the epoch of intrusion.

Prof. F. D. Adams[1] has described a number of Canadian gneisses, some of igneous origin and affected by dynamic metamorphism, others sediments altered by thermal metamorphism, and he has pointed out criteria for discriminating the two.

Although we have distinguished primary and secondary banding and foliation in plutonic rocks, the alternatives numbered (ii) and (iii) above are by no means mutually exclusive in application to any given rock, and a gneiss of primary igneous origin may present phenomena due to subsequent dynamic metamorphism.

In the South Indian 'charnockites' (pyroxene-gneisses or pyroxene-granulites of some authors), already referred to under the head of hypersthene-granite, Mr Holland has shewn that the frequent banding and foliation are primary, but dynamic effects are also indicated, notably in the production of garnet. Lacroix[2] noted that in these rocks the felspars are often crowded with little round or elongated inclusions of quartz ('quartz de corrosion' of French writers) without the regularity of a graphic intergrowth. This is ascribed to secondary corrosion.

The associated basic rocks present in some cases more difficult problems. Here are found curious micrographic intergrowths between the ferro-magnesian minerals (pyroxene, hornblende, garnet) on the one hand and felspar and quartz on the other. Lacroix finds scapolite a characteristic constituent of the 'pyroxene-gneisses' here and in other districts[3].

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[1] *Ann. Rep. Geol. Sur. Can.* (1895) viii, 31–81 J, pl. IV, v.

[2] *Rec. Geol. Sur. Ind.* (1891) xxiv, 157–190.

[3] *Cf.* Judd and Brown, *Proc. Roy. Soc.* (1895) lvii, 391 ; *Phil. Trans.* (1896) clxxxvii, *A*, 193–204, pl. VI (Burma).

Granulites. (Fr. leptynites[1].) The granulites are fine-textured crystalline rocks consisting of quartz, felspars, and various other minerals, among which garnet is highly characteristic. They shew a remarkable uniformity of grain among the several constituents. There is often a more or less evident parallel orientation of the elements, but no schistosity. Such an even-grained mosiac we have already noticed in some of the products of extreme thermal metamorphism and again in the rocks resulting from the 'granulitization' of crystalline masses in connection with crushing, while somewhat similar features are found in rocks formed directly from igneous fusion. Indeed any petrographical definition of granulite will be found to cover rocks having quite different origins.

It will be sufficient to notice briefly some of the characters of the more or less indefinite group of rocks known as granulites in Saxony and other parts of Europe, where they attain a very considerable development. These rocks have provoked much difference of opinion, but it is now generally believed that many of them are of igneous origin, while they often bear evidence of the operation of mechanical forces either during or after their formation. The varieties of most common occurrence are acid rocks, but there is also a division of basic composition (pyroxene-granulite, or Trapp-granulit of some German writers).

The former contain, in addition to quartz, various alkali-felspars—orthoclase, microcline, and plagioclase, with sometimes microperthitic intergrowths. Dark mica is commoner than white as an original constituent, but red garnet is more prominent than either in the usual types of granulites. All these minerals occur in little irregular grains, usually clear except for inclusions of earlier formed constituents. Cyanite, in rude crystals, sillimanite prisms or aggregates (fibrolite), green hornblende, tourmaline, and other minerals may occur, and are taken as marking different types (cyanite-granulite, tourmaline-granulite, etc.). Many of these rocks also contain

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[1] The 'granulite' of French writers signifies a granite with white and dark micas.

garnet; and garnet-granulite, in which that mineral is the characteristic one, is the most familiar type (Chemnitz district in Saxony, Wartha in Bohemia, Nanniest in Moravia, 'leptynites' of the Vosges, *etc.* : see fig. 81).
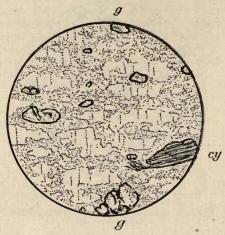
FIG. 81. GARNET-GRANULITE, RÖHRSDORF, NEAR CHEMNITZ, SAXONY; × 20.

Shewing grains of garnet (*g*) and imperfect prisms of cyanite (*cy*) set in a granular aggregate of felspar and quartz. The latter shews a parallel arrangement of its larger elements, and there are rows of fluid-pores traversing the rock at right angles to the parallel-structure [835].

The pyroxene-granulites are rich in irregular, often rounded, grains of pyroxene in addition to quartz, plagioclase (usually not orthoclase), often garnet, biotite, and magnetite. The pyroxenes include apparently both hypersthene and a pleochroic (pink to pale green) augite closely resembling it (Mohsdorf, Hartmannsdorf, *etc.*, in Saxony).

A frequent peculiarity in all the granulites is the occurrence of what have been styled *centric* structures[1], of which

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[1] Cohen (3), pl. xxxviii, figs. 1, 2.

the most usual take the form of aggregates of various con-
stituents about the grains of garnet, or radial groupings of
such minerals as pyroxene or hornblende, with or without
a garnet in the centre (*cf.* fig. 82).
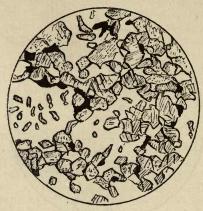
FIG. 82.   PYROXENE-GRANULITE, CHEMNITZBACH, NEAR MOHSDORF,
SAXONY;   × 20.

Much of the pyroxene is hypersthene : the clear portion of the slice
is a mosaic of plagioclase felspar and quartz.   The rock shews a rude
'centric' structure in the arrangement of the pyroxene-grains [494 *a*].

In granulites having an evident parallel-structure there
are often lines of fluid-pores arranged transversely to that
structure and passing through the quartz and felspar alike
(fig. 81).   This may be noticed as a well-known strain-effect.
Strain-shadows in the crystals are not often observed in
granulites.   In some of the rocks (Ger. Augengranulit) there
are 'eyes' consisting of larger lenticular individuals of felspar
or quartz-felspar aggregates.

Of rocks which may be petrographically described as
granulites numerous examples are found in the Scottish
Highlands.   Garnet-granulites are represented, one type con-
sisting of quartz, felspars, garnet, and biotite, with a little
muscovite, sphene, and magnetite (*e.g.* Beinn Wyvis).   Actin-

olite-granulites occur, shewing long imperfect prisms of green actinolite in a clear even-textured mosaic of untwinned felspar and quartz, with a little magnetite and small flakes of biotite (Strathan near Lochinver).

Pyroxene-granulites are also found : one type consists of diallagic augite, sometimes hypersthene, and abundant clear plagioclase, with some biotite and magnetite. Garnet is only sparingly present, and there is very little quartz (Badenaban near Lochinver). Professor Cole[1] has figured a pyroxene-granulite with hypersthene and garnet from near Huntley, Aberdeenshire.

Eclogites. Among rocks of somewhat doubtful affinities must be mentioned the small group of the eclogites. The typical eclogite of Haüy consists essentially of an aluminous augite (omphacite) and red garnet, with sometimes quartz, hornblende, actinolite (smaragdite), cyanite, or other accessories. From their mode of occurrence, the rocks are commonly regarded as of true igneous origin.

The dodecahedral or rounded crystals of *garnet* are quite pale in thin slices. They contain various inclusions, such as quartz granules (collected in the centre of the crystal), needles of cyanite[2] or rutile (ranged in rows parallel to the faces of the dodecahedron), little prisms of zircon, *etc.*

The green *omphacite* is nearly colourless in slices. It builds columnar crystals, which, when moulded by quartz, may have good faces, but usually build an irregular aggregate or shew a parallel arrangement. Besides the prismatic cleavage there may be one parallel to the orthopinacoid, or a slight diallagic structure. The extinction-angle rises to 40° or more. Inclusions of rutile, *etc.*, are found, and sometimes a parallel intergrowth of bright green *smaragdite*. Some eclogites contain a pale yellowish green *bronzite* : this forms idiomorphic crystals.

Clear *quartz* is usually present ; *biotite* flakes sometimes cling about the garnet crystals ; while *cyanite*, zoisite, glauco-

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[1] *Aids in Pract. Geol.* (1891) p. 210.
[2] *G. M.* 1891, 170, 171 (Port Tana, Norway).

phane, zircon, rutile, *etc.*, may be seen in some examples. Iron-ores are not abundant.

The omphacite makes up the bulk of the rock, forming a crystalline aggregate in which the garnet is embedded, while quartz is always of interstitial occurrence. A clear ring or shell of the last mineral is often interposed between each garnet and the surrounding omphacite. Again, the garnet is sometimes broadly bordered by a 'celyphite'-growth with
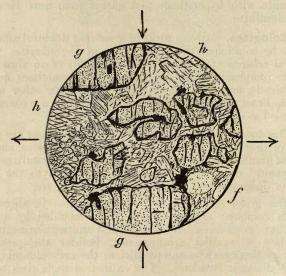
FIG. 83. HORNBLENDE-ECLOGITE (GARNET-AMPHIBOLITE), LOCH LAXFORD, SUTHERLAND; × 15.

Consisting of red garnet (*g*) and green hornblende (*h*), with only a little clear quartz, turbid felspar (*f*), and opaque iron-ore. The arrows shew the directions of the stresses that have operated in the rock, and the brittle garnets are traversed by a strongly marked system of cracks perpendicular to the direction of tension [1254].

radial or plumose arrangement and of varying constitution. In a Bohemian example (Chlumiček) it consists of radiating

bundles of enstatite prisms : in other cases actinolite, biotite, and other minerals take part in the celyphite-border.

The best known eclogites are from Bavaria[1] (Eppenreuth, with cyanite, *etc.*, Silberbach), the Saxon Granulite Mountains (Waldheim, with sphene), Silesia (Frankenstein, with zoisite supposed to be derived from the garnet), the Pennine Alps (Val d'Aoste[2], with glaucophane), Carinthia (Saualp[3], with zoisite), the island of Syra (with glaucophane), *etc.* Good examples of eclogite occur in the district of Loch Duich and Glenelg, on the west coast of Scotland ; and one of these, from Totaig, has been described by Mr Teall[4]. This contains green hornblende, partly surrounding the garnet, and, instead of quartz, a plagioclase felspar occurs in small quantity interstitially or in micrographic intergrowth with the omphacite. A rock comparable in many respects with eclogite is recorded from Mountain Lodge, near Pettigo, Donegal[5].

Closely allied to the typical eclogites are the rocks styled garnet-amphibolite ; in which hornblende more or less completely takes the place of omphacite. Such rocks are found in Norway, Silesia, and other areas. Prof. Bonney[6] has described one from Beinn Fyn, near Loch Maree, under the name *hornblende-eclogite*. It consists mainly of garnet and green hornblende with some quartz, plagioclase, *etc.* A handsome rock having the same general characters occurs near Loch Laxford, in Sutherland[7] (fig. 83). It will be seen that the only members of the eclogite group yet recognized in Britain are all associated with the old gneisses of the Highlands. A rock consisting of garnet and greenish brown hornblende, with grains of rutile, has been noted from Santa Catalina Is., Cal.[8]

[1] Newland, *Trans. N.Y. Acad. Sci.* (1897) xvi, 24–29 ; Cohen (3), pl. xvii, fig. 1.

[2] Bonney, *M. M.* (1886) vii, 1–3, pl. i, and *Phil. Mag.* (1892) xxxiii, 244.

[3] Cohen (3), pl. xxi, fig. 1.

[4] *M. M.* (1891) ix, 217, 218.

[5] Cole, *Tr. Roy. Ir. Acad.* (1900) xxxi, 457, 458, pl. xxvi, fig. 6.

[6] *Q. J. G. S.* (1880) xxxvi, 105, 106.

[7] *G. M.* 1891, 171, 172.

[8] W. S. T. Smith, *Pr. Cal. Acad. Sci.* (1897) i, 62–64.

In a French hornblende-eclogite, a local modification of a diorite, the hornblende is light brown[1]. In other examples the amphibole is a glaucophane with vivid blue and violet pleochroism (Val d'Aoste in Pennine Alps, Ile de Groix in Brittany)[2].

[1] Fouqué and Lévy, pl. vi.
[2] Bonney, *M. M.* (1886) vii, 1–7, 150–154, pl. i.

INDEX.

[Some rock-names are given here which are not admitted into the text. The list will thus serve to some extent as a glossary.]

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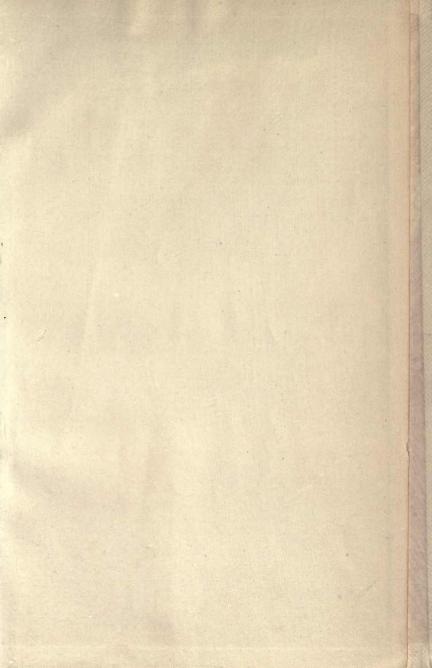
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